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GRAND RIVER BASIN WATER MANAGEMENT STUDY

TECHNICAL REPORT SERIES
REPORT #29

EFFLUENT MIXING ZONE STUDIES

PREPARED FOR THE GRAND RIVER IMPLEMENTATION COMMITTEE BY

L. E. Post
T. P. Halappa Gowda

Project Leader
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October, 1985
Water Resources Branch
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FOREWORD

The report "Effluent Mixing Zone Studies" is one of a series of technical documents prepared for the Grand River Basin Water Management Study. The project described herein was undertaken through the Grand River Study Team at the request of the Grand River Implementation Committee.

The material contained in these reports is primarily technical support information and, in itself, does not necessarily constitute policy or management practices. Interpretation and evaluation of the data and findings, in most cases, cannot be based solely on this one report but should be analyzed in light of other reports produced within the comprehensive framework of the overall study. Questions with respect to the contents of this report should be directed to D.G. Weatherbe, P.Eng., Supervisor, River Systems Assessment Unit, Water Resources Branch, 135 St. Clair Avenue West, Toronto, Ontario, M4V 1P5.

EXECUTIVE SUMMARY

One of the concerns of the Grand River Basin Water Management Study is the need to define the toxic effect areas of chlorine and ammonia from wastewater effluent. This is accomplished by the delineation of a "mixing zone" or "limited use zone" in a portion of the cross-section of river below the outfall, where concentrations of the pollutants may not comply with the provincial water quality objectives (PWQO). The remaining portion of the cross-section of the river, where the water quality is suitable for maintaining aquatic life, is termed the "zone of passage". Water management policies of the Ministry of the Environment (MOE) allow the use of mixing zones provided terms and conditions governing the size and water quality within the mixing zone are met. These provisions are stipulated in the MOE publication "Water Management (MOE, 1978)".

A two-dimensional mathematical model was used to determine limited use zones and zones of passage attainable in individual mixing zones of receiving streams under present and future loading conditions for the various management options considered in the long-range planning study. The model incorporates longitudinal convection, lateral dispersion and first-order decay of a nonconservative pollutant. In this study, five wastewater treatment plants were considered: Waterloo, Kitchener, Galt, Brantford, and Guelph. Effluents from the first four plants are discharged into the Grand River; the Guelph plant discharges its effluent into the Speed River. The two-dimensional model was not applied to the Brantford case since the effluent was observed to spread across the entire width of the Grand River in a short distance below the outfall. For the other four cases, the reductions in effluent concentrations required to obtain desired zones of passage were calculated for specific design conditions (e g. effluent flow rates and concentrations of chlorine and ammonia, various river flow rates and a lateral boundary of the limited use zone equal to 40% of river flow rate). For the Brantford case, concentrations of un-ionized ammonia and chlorine were predicted using the instantaneous completely mixed assumption.

Results of the mixing zone study indicated that within the study areas of the Grand River Basin, for the design cases considered, a zone of passage having a lateral boundary consisting of 60% of the total river flow is attainable with regard to chlorine toxicity. Only after the 2001 medium projected population level at Guelph, under low flow winter conditions, would the PWQO for chlorine be in noncompliance in the Speed River.

In order to achieve the PWQO for un-ionized ammonia, tertiary treatment is necessary at the Waterloo wastewater treatment plant. With the implementation of tertiary treatment at Kitchener, the PWQO for un-ionized ammonia can be achieved until 2031 (summer low flow); however, with advanced treatment (activated carbon absorption), no violations of the PWQO would occur. Current tertiary treatment at the Guelph plant is not sufficient for maintaining the necessary zone of passage in the Speed River, based on the PWQO for un-ionized ammonia. At Galt, no additional treatment over the conventional activated sludge is necessary to maintain satisfactory levels of un-ionized ammonia in the river.

In the case of the Grand River below the Brantford wastewater treatment plant, results based on the instantaneous completely mixed assumption indicate that residual chlorine would have a minimal effect (extending approximately 20 m downstream of the outfall), whereas un-ionized ammonia concentrations may not be in compliance with the PWQO for downstream distances of 124 m to 2239 m under different conditions of streamflow and temperature.

ACKNOWLEDGEMENTS

Assistance in modelling was provided by Mr. K. Willson of the Water Resources Branch, Ministry of the Environment. Mr. M. Fortin provided assistance on data presentation and Dr. I. W. Heathcote reviewed the manuscript. Assistance with drafting by Ms. J. Barnes and Ms. K. Simpson is gratefully acknowledged.

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I. INTRODUCTION

1.1 General

Wastewater effluents discharged into receiving streams and rivers often contain substances such as chlorine and ammonia which are potentially toxic to aquatic biota. Other water uses such as recreation, agriculture and withdrawals for drinking water supply can also be affected by toxic levels of such pollutants. In order to minimize the potentially toxic effects of such pollutants, effluents are generally discharged through bank outfalls so as to create a plume that hugs a shoreline of the river.

Due to the geometric and hydraulic characteristics of an outfall and of a receiving watercourse, transverse and longitudinal variations of concentrations of the toxic pollutants occur as the effluent moves downstream from the point of discharge. The zone of a river between the outfall and the nearest cross section where the instream mixed concentration attains uniformity is termed the "mixing zone".

In order to provide a favourable habitat for the biota within a mixing zone, it is desirable to maintain a specific portion of the cross section of the receiving stream wherein the concentrations of the pollutants comply with a specified water quality objective (C_s). The portion of the stream in which the water quality is considered suitable for the maintenance of aquatic life is termed the "Zone of Passage" (ZOP). The remaining portion of the river where the pollutant concentration may not comply with the specified objective is termed the "Limited Use Zone" (LUZ). The salient features of a mixing zone are depicted in Figure 1 (Gowda, 1980a and 1980b). The policies and guidelines describing the use of mixing zones is presented in the publication "Water Management" (MOE, 1978).

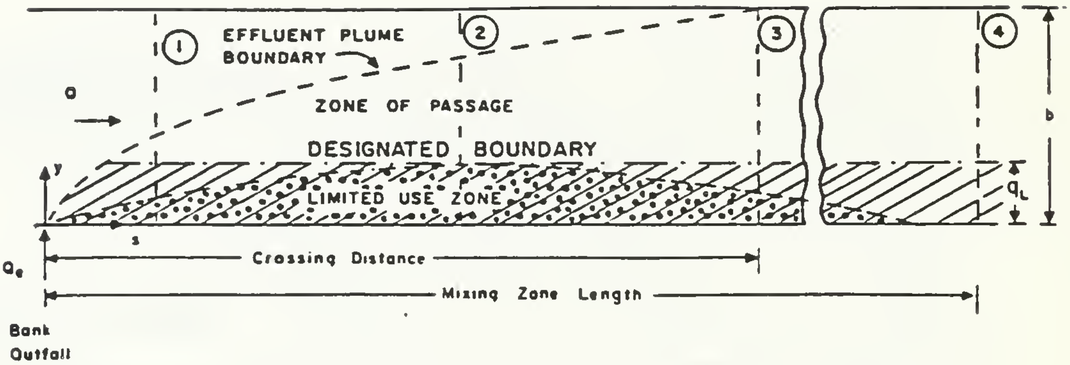


Figure 1. Salient features of a Mixing Zone in a River. (Note: Cross-sections 1 - 4 refer to Figure 3).

One of the concerns of the Grand River Basin Water Management Study (GRBWMS) is the maintenance of zones of passages in river channels below the major wastewater treatment plants in the megalopolis region of the Grand River Basin. Of particular concern are the potential problems of chlorine and ammonia toxicity to the aquatic biota which inhabit the rivers below the treatment plants.

This study describes the application of a two-dimensional steady state mathematical model which incorporates advection, lateral dispersion and decay of a pollutant to predict instream concentration distributions of chlorine and ammonia for the various management options being considered in the long-range river basin planning study. The results presented in this report should be considered as indicative only of general, relative trends in water quality changes resulting from various management options. Given the data limitations outlined within the report, detailed field and modelling studies at appropriate implementation stages are recommended.

1.2 Objectives

The main goal of this study is to assess the ability of the various management alternatives to provide a zone of passage with respect to the provincial surface water quality objectives for chlorine and ammonia. The specific objectives of the study are as follows:

a) To determine if a specified ZOP for aquatic biota is attainable with respect to toxicity of total residual chlorine and of ammonia, under present and future loading conditions, by maintaining the present concentrations of the pollutants in the effluents.

b) To determine if the ZOP is attainable under present and future loading conditions for the various management options (producing various effluent pollutant concentrations) considered in the long-range planning study.

c) To estimate the allowable effluent concentration of each pollutant so as to achieve the required ZOP.

d) To estimate the maximum longitudinal boundary at which the specified water quality objective for each pollutant is achieved.

1.3 Pollutants Considered and Their Toxicity

Current wastewater treatment practices for mechanical plants within the Province of Ontario require effluent disinfection, generally through chlorination, before an effluent can be discharged into a receiving water body. Residual chlorine present in the chlorinated effluents is potentially toxic to aquatic biota. The toxicity component of residual chlorine is usually expressed in terms of Total Residual Chlorine (TRC), which is given by the sum of free ($HOCl$ and OCl^-) and combined (chloramines) forms. Ammonia is commonly present in municipal wastewater effluents in both ionized (NH_4^+) and un-ionized (NH_3) forms, the fraction of each being dependent on the pH and temperature of the receiving water. The un-ionized portion of total ammonia is potentially toxic to aquatic biota.

In order to ensure a satisfactory level of water quality in surface water bodies, the Ministry of the Environment (1978) has published a set of objectives termed "Provincial Water Quality Objectives" (PWQO). In general, the instream concentration of a pollutant discharged into a receiving water body should comply with the PWQO for that pollutant to ensure protection of aquatic life, recreation, and other uses. When a limited use zone is utilized for dilution of the effluent, the specified instream water quality objective, C_S, must be met at a given lateral boundary of the LUZ, in order to ensure a zone of passage for fish and other biota. The PWQO for total residual chlorine and un-ionized ammonia are 0.002 mg/L and 0.02 mg/L, respectively (maximum daily permissible concentration).

The Ministry's Surface Water Policy 1 (1978) states that in areas where water quality is better than the PWQO, the water quality must be maintained at or above the objectives. Policy 2 states that for areas where water quality does not currently meet the objectives, no further degradation may be incurred and all practical measures should be taken to upgrade water quality.

Therefore, the intended goal of any management scenario is to achieve the PWQO. In view of the fact that these objectives are not always achievable, particularly for surface waters currently in non-compliance with the PWQO (as outlined in Policy 2), alternative management plans which could achieve an improvement in surface water quality or at the very least do not further degrade surface water quality need to be examined.

1.4 Water Pollution Control Plants

This study considers individual mixing zones in rivers below four major water pollution control plants (WPCP) - three on the Grand River, viz., Waterloo, Kitchener and Galt, and the Guelph WPCP on the Speed River (Figure 2). The present treatment level and the design hydraulic capacity of each plant is presented in Table 1.

TABLE 1: PRESENT TREATMENT LEVEL AND CAPACITY FOR FIVE WPCP'S WITHIN THE GRAND RIVER BASIN

WPCP	TREATMENT LEVEL*	HYDRAULIC CAPACITY	
		MGD	m^3/sec
Waterloo	1	10.0	0.44
Kitchener	1	27.0	1.18
Guelph	2	12.5	0.55
Galt	1	8.5	0.37
Brantford	1	18.5	0.81

* Treatment Level 1 is conventional activated sludge only; and Level 2, known as tertiary treatment, is a conventional activated sludge plant with rotating biological discs for nitrification and sand filters for effluent polishing. Effluent chlorination is practiced at each WPCP.

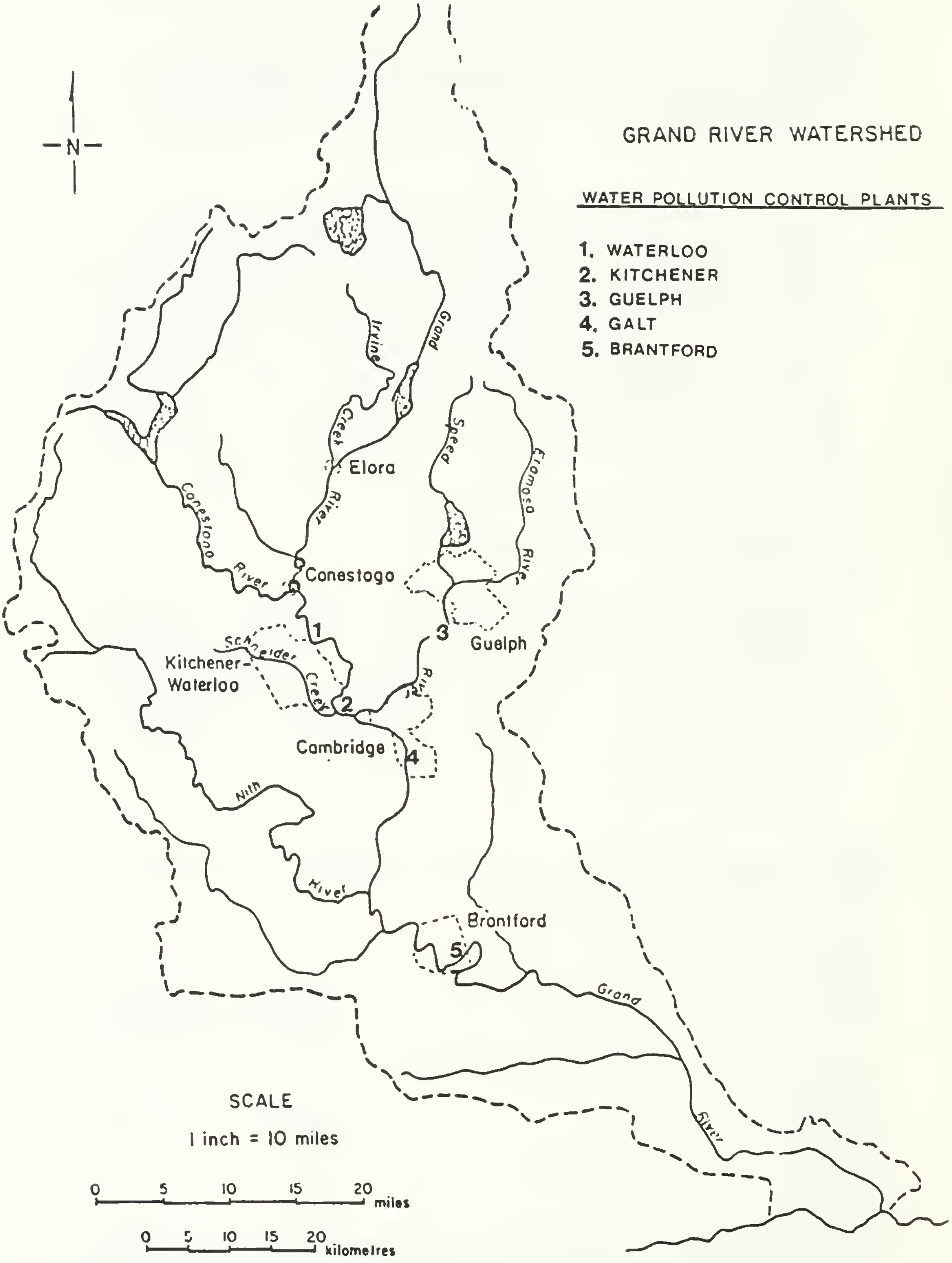


Figure 2. Locations of the Water Pollution Control Plants under study within the Grand River Basin.

The two dimensional mixing zone model utilized in this study is designed for a shore-attached effluent plume below a bank outfall in a river, and has been applied to the locations below Waterloo, Galt and Guelph. The actual outfall for the Kitchener wastewater treatment plant is located in the middle of the river. Field studies carried out at this location during 1975 and 1979 have shown that the released effluent moves towards the right bank (looking upstream), encounters a riffle, then crosses the river to the left bank at a 45^{0} angle, thus creating a potentially toxic barrier. The effluent then tends to hug the left bank as it continues to move downstream. Since the mixing zone model requires a bank outfall, the point of discharge has been assumed to be located at the left shoreline, below the riffle (about 300 m downstream of the present location) for modelling purposes.

In the case of the Brantford Wastewater Treatment Plant, the effluent mixes completely across the river in a short distance below the bank outfall. Therefore, the two dimensional model (applicable to shore-attached effluent plumes) was not applied to the Brantford case. However, instream concentrations of un-ionized ammonia and chlorine have been predicted based on the instantaneous complete mixing assumption and are presented in this report.

The model only considers the effects of pollutant concentrations in the effluent of the wastewater treatment plants under study. Background concentrations of pollutants were not incorporated into the model predictions.

II MODELLING ASPECTS

2.1 Stream Tube Model

2.1.1 Description of Model:

The basic concept of the stream tube model, developed by Yotsukura and Cobb (1972), is the utilization of partial cumulative discharge, q, at a given cross-section of a river as the independent variable in the analysis. Hence the river is divided into a number of vertical strips termed "stream tubes", such that the discharge within each strip is the same. This transformation conveniently accounts for the solute mass balance and adequately approximates natural stream conditions resulting from variable widths and velocities (Yotsukura & Cobb, 1972). Cross-sectional concentration distributions, c(x, q), predicted by the streamtube model will therefore be functions of q rather than the normally used transverse distance, y. The details of the derivation of the streamtube model have been presented by Yotsukura (1977), Yotsukura and Sayre (1976) and Yotsukura and Cobb (1972). Modifications of the stream tube model equations to account for longitudinal variabilities in decay rate coefficients and hydraulic parameters of river channels are presented by Gowda (1980b). The derivations of these analytical expressions are beyond the scope of this report, but are available in the above citations. However, the important aspects of the model are briefly described in the following sections. All computational procedures are applicable to shore-attached plumes in shallow rivers resulting from effluent discharge at bank outfalls.

2.1.2 Limited Use Zone Boundary

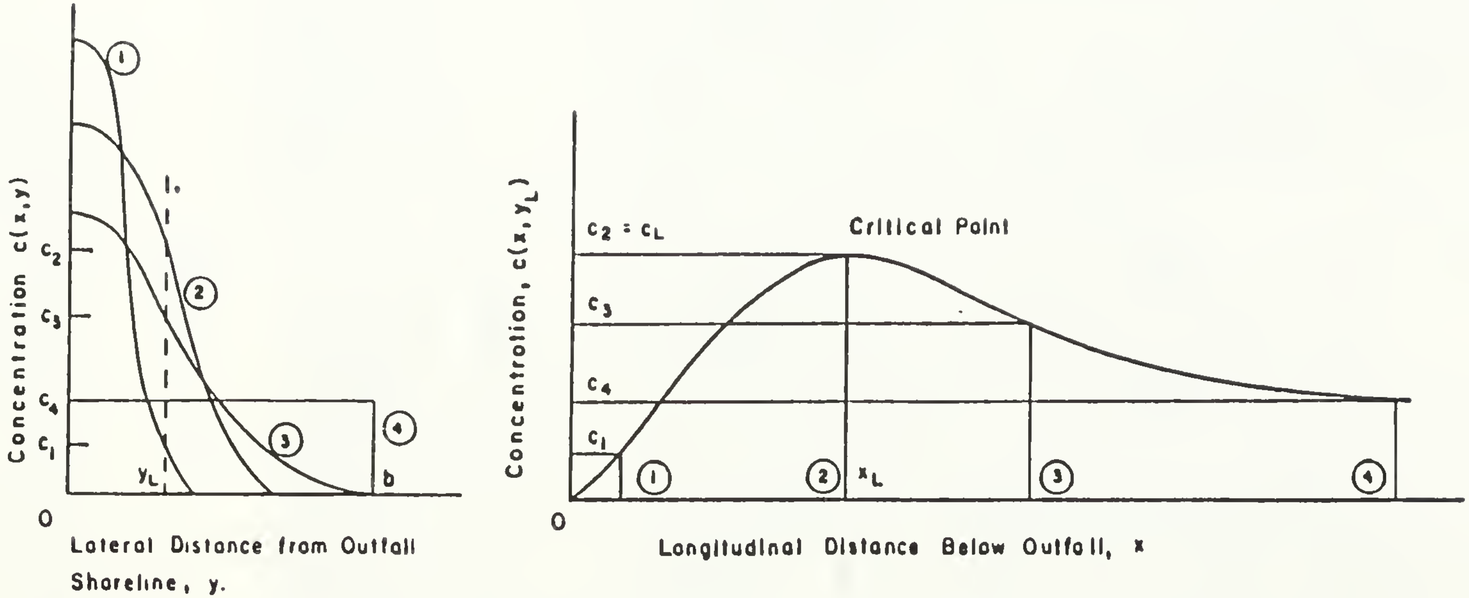
In order to maintain an acceptable zone of passage, the lateral boundary of a LUZ is limited to some specified fraction of the total river flow. The partial cumulative discharge between the outfall bank and the accepted LUZ lateral boundary is denoted by q_L. The specified instream water quality objective, C_S, must be met at the lateral boundary, q_L, at all downstream distances below the outfall. Instream concentrations of a particular pollutant for a given $q = q_L$ increase to a maximum at some value of x and then decrease as shown in Figure 3. The point at which the concentration reaches a maximum value is termed the "critical point". The concentration at this critical point is termed the "critical concentration", C_L, and the distance downstream of the outfall to the critical point is termed the "critical distance", X_L. Methods of determining X_L and C_L are described in other publications (Gowda, 1980a and 1980b). The co-ordinates of a critical point for a given q_L are used to calculate allowable effluent concentrations as explained in the following sub-section. The longitudinal boundary of a LUZ occurs at the first downstream point along the effluent shoreline where the water quality objective, C_s is met.

2.1.3 Allowable Effluent Concentration

Once the critical concentration, C, for a given q_L is known, the allowable effluent concentration, C_{eA}, can be calculated according to the following equation (Gowda, 1980a):

$$C_{eA} = \frac{C_e C_s}{C_L} \qquad (1)$$

C_e = concentration of pollutant in effluent
C_s = specified instream concentration criterion
C_L = critical (maximum instream) concentration for a given q_L


Concentration c(x,y)
c_2
c_3
c_4
c_1
0
①
②
③
④
y_L
b
Lateral Distance from Outfall Shoreline, y.
Concentration, $c(x, y_L)$
$c_2 = c_L$
Critical Point
c_3
c_4
c_1
0
①
②
x_L
③
④
Longitudinal Distance Below Outfall, x

(a) CONCENTRATION PROFILES AT CROSS-SECTIONS ① TO ④

(b) LONGITUDINAL PROFILE ALONG A LATERAL BOUNDARY OF LIMITED USE ZONE.

Figure 3. Pollutant Concentration Profiles in Mixing Zones.

When C_{eA} is less than C_e, a reduction in the effluent concentration, C_e, is required. When C_{eA} is greater than C_e, the stream is capable of assimilating an effluent concentration higher than C_e.

2.2 Computational Aspects

A computer model MIXAPPLN, written in FORTRAN language, has been developed using the stream tube model equations to perform design case computations. A documentation for the program taken from Gowda (1980b) is provided in Appendix A. A brief description of the program is provided below.

Data on channel hydraulics and pollutant decay rates obtained from field surveys, along with design case options, are input into the model to produce a matrix of concentrations for cumulative values of q at various distances below the outfall. Through an iterative procedure, the program calculates allowable effluent concentration and maximum longitudinal spread (i.e., longitudinal boundary of LUZ) for a given set of input data.

Concentrations at any distance, x, downstream of the outfall are calculated according to the following relation:

$$C(x, q) = (0.5)(C_a)(RF)(SUM)/(\pi\theta)^{1/2} \qquad (2)$$

C_a = cross sectional average concentration in river just below outfall.

RF = decay function, which accounts for reach-dependency of the decay rate including temperature effects.

$\theta = B' \frac{(X)}{(B)}$, where

B' = nondimensional coefficient (accounting for variations in channel geometry and transverse dispersion characteristics), determined from field data and model calibration study.

X = downstream distance from outfall (m).
B = width of channel at distance X (m).
SUM = a term to account for the effects of lateral dispersion and sidewall reflection of pollutant on $C(x, q)$

Figure 4 depicts graphically the iterative process utilized by the program to calculate C_{eA}. The concentration distributions predicted by Equation 2 are utilized to search for the transect at which the concentration is maximum for a given q_L. Using this concentration, C_{crit}, and the associated downstream distance, X_{crit}, along with the weighted mean values of width and velocity as first estimates, new values of C_L and X_L are calculated. If the absolute percentage difference $(100\ (X_L - X_{crit})/X_L)$, is greater than an arbitrarily chosen percentage, the procedure is repeated until the difference is within the specified limit. For the purpose of this study, the acceptable difference was chosen to be 5%. The values obtained in the final iteration step are then printed out as the critical concentration, C_L, and critical distance, X_L, for a given q_L. Knowing C_L and C_S, the allowable effluent concentration, C_{eA}, is calculated according to Equation 1.

NOTE: In the program listing (Appendix A), taken from Water Resources Paper #14 (Gowda 1980b), the dimensionless term θ has been modified by replacing B with BW, where BW denotes the moving average value of channel width for the distance, X, downstream of the outfall. The coefficient, B', was replaced with a dimensionless coefficient, B", where $B'' = B'(BW/B)$. A comparison of the predictions of the two computer program versions for the case of total ammonia in the Grand River below Waterloo indicated differences in C_{eA} of up to 0.4 mg/L (as N) and in maximum longitudinal spreads of up to 300 meters. Predicted values for longitudinal spread given in Water Resources Paper #14 are consistently lower than those presented in this report. On the other hand, predicted concentrations in the former publication are higher than those in this report.

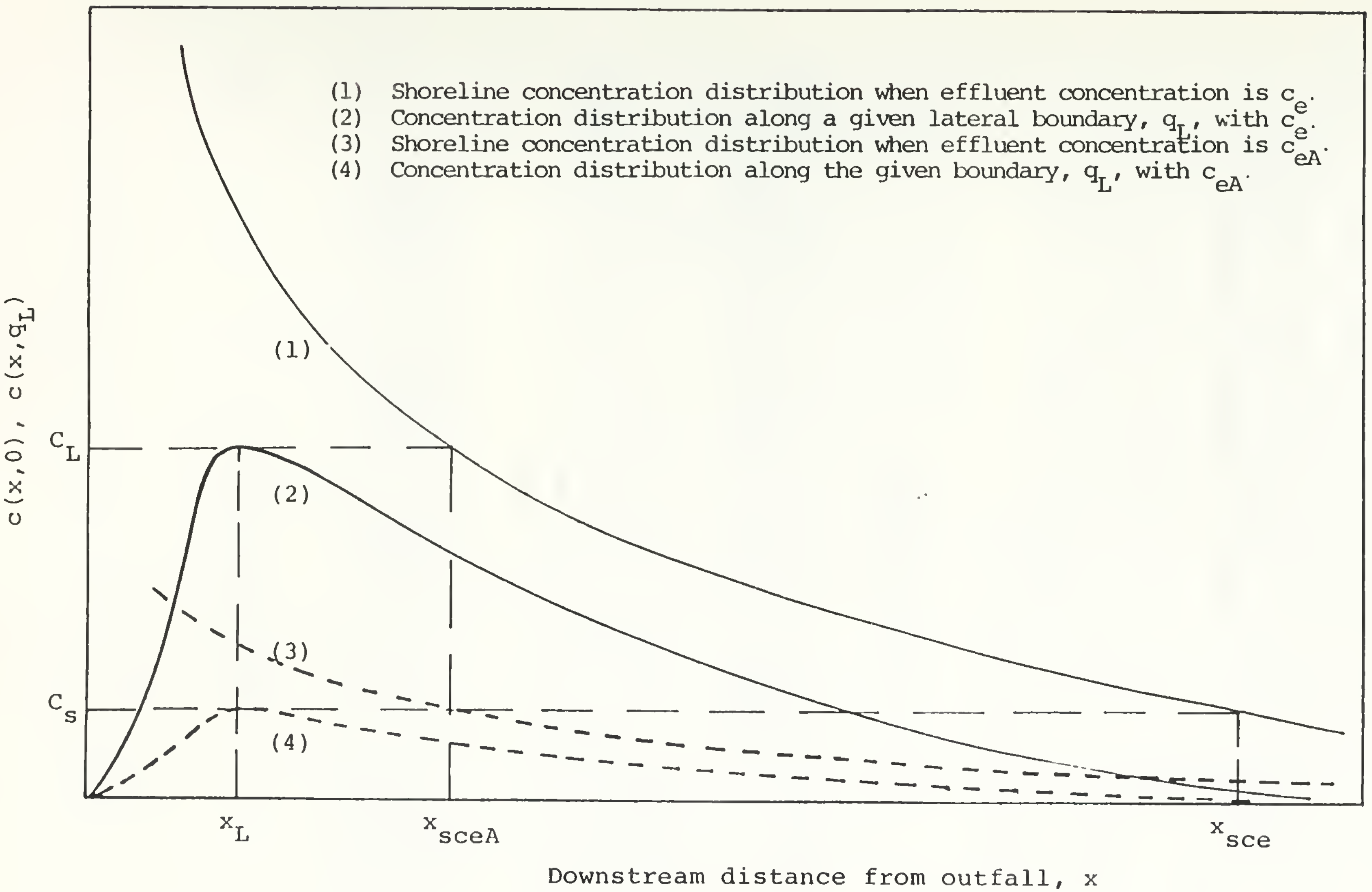


Figure 4. Graphical Representation of Iterative Procedure

When the effluent is discharged from a bank outfall, the maximum concentrations at various transects within the mixing zone occur along the outfall shoreline ($q = 0$). In order to determine the downstream distance along the shoreline where the instream water quality objective is met, the program searches for the transect where the predicted shoreline concentration is just above C_S. The program then iterates in a similar manner as outlined above to determine the corresponding distance, X_{sce}, where C_S is met.

In addition, the model also performs a similar iterative procedure to determine the downstream shoreline distance X_{sceA}, where the instream water quality is met when the effluent concentration is C_{eA}.

2.3 Scale-up of Model Parameters

In order to assess present and future water quality within the Grand River Basin with regard to chlorine and ammonia toxicity, various management options have been examined (see Chapter III). These options include treatment plant expansion, flow augmentation, and seasonal variabilities in streamflow and temperature. Changes in design temperature and design streamflow would require a scale-up of model parameters (width, depth, velocity, etc.) to account for the variabilities associated with the various options.

The decay rates of total residual chlorine and ammonia are dependent on temperature and are adjusted in the MIXAPPLN program according to the modified Van't Hoff-Arrhenius relationship given by

$$K_{T2} = K_{T1} \theta^{T_2 - T_1} \qquad (4)$$

K_{T1}, K_{T2} = decay rate coefficients at temperatures T_1 °and T_2 °C, respectively; and θ = temperature correction factor. Values of θ for TRC and ammonia were set equal to 1.03 and 1.106, respectively (Gowda, 1978; Eckenfelder, 1970).

Changes in streamflow rates result in corresponding changes in channel width, depth and velocity. The computer model utilizes the Leopold-Maddock equations to acount for the changes in hydraulic parameters (Eckenfelder, 1970). For example, a width B(2) resulting from a streamflow Q(2) is calculated by

$$B(2) = B(1)\left\{\frac{Q(2)}{Q(1)}\right\}^{BPWR} \qquad (5)$$

Q(1) = measured flow

B(1) = measured width corresponding to Q(1)

BPWR = empirically derived constant

A more detailed description of scale-up procedures is provided in other publications (Gowda, 1980a and 1980b).

III EVALUATION OF MANAGEMENT OPTIONS

3.1 Options Modelled

The various management plans under consideration for the Grand River Basin are fully described in Smith (1981) and Willson _et al_ (1981). The various options and the design parameters associated with each option are presented below (subsections 3.1.1 - 3.1.5). These values are used as inputs to the mixing zone model, along with instream process parameters (see subsection 3.1.6).

3.1.1 Effluent Flow (QEFL)

Present and future water quality depends on changes in effluent loading rates relating to projected population increases in the major urban centres. The effects of projected increases in populations and resultant pollutant loads for 20 and 50 year planning periods beginning with 1981 (i.e. years 2001 and 2031) are incorporated into the model in terms of effluent flow rates (QEFL). The projected population for the year 2001 is a medium density, while both medium and high density populations were projected for the year 2031 (to account for possible changes in future growth). The effluent flows utilized in this study are summarized in Table 2.

TABLE 2: EFFLUENT FLOWS (QEFL)

	WATERLOO		KITCHENER		GUELPH		GALT		BRANTFORD	
YEAR	cfs	m^3/s	cfs	m^3/s	cfs	m^3/s	cfs	m^3/s	cfs	m^3/s
1979	10.86	0.31	23.70	0.67	18.20	0.52	9.09	0.26	17.35	0.49
2001M*	21.22	0.60	39.28	1.11	27.92	0.79	17.43	0.49	24.55	0.69
2031M	30.62	0.87	56.26	1.59	50.70	1.43	25.02	0.71	37.37	1.06
2031H**	35.21	1.00	64.86	1.84	66.18	1.87	28.77	0.79	46.67	1.32

* M: Medium density population

** H: High density population

3.1.2 Upstream Flows (QRUP)

The 7-consecutive-day low flow with a 20-year return period (7Q20) under natural unregulated discharge conditions is approximately 1.1 m^3/sec (40 cfs) in the Grand River at Bridgeport. There are two existing reservoirs on the Upper Grand River, namely Lake Belwood and Lake Conestoga. The river discharge is currently augmented by approximately 8.5 m^3/s (300 cfs) from the two reservoirs from spring until fall. The river discharge is approximately 1.1 m^3/sec (40 cfs) during winter since no augmentation occurs due to the low reservoir levels.

Six upstream flow rates in the Grand River at Bridgeport are considered in the design cases, based on the following management conditions:

Design Flow

1:	1.1 m^3/sec (40 cfs)	winter flow (7Q20).
2:	4.2 m^3/sec (150 cfs)	higher winter flow resulting from warm wet winter or the use of reservoirs during spring-fall strictly for maintaining flood control rather than flow augmentation.
3:	8.5 m^3/sec (300 cfs)	the present target of 350 cfs
4:	11.3 m^3/sec (400 cfs)	summer low flow at Doon.
5:	14.2 m^3/sec (500 cfs)	incorporates the construction of the West Montrose reservoir to maintain water quality in future through flow augmentation.

6:	17.0 m^3/sec (600 cfs)	incorporates the building of both the West Montrose and the St. Jacobs Reservoirs for flow augmentation.

The Speed River currently has one reservoir located above the City of Guelph. Three river flows upstream of Guelph are considered in the design cases:

Design Flow

1:	0.5 m^3/sec (17 cfs)	unregulated natural flow at Guelph (7Q20).
2:	1.8 m^3/sec (64 cfs)	present flow with augmentation from the Guelph reservoir.
3:	2.5 m^3/sec (88 cfs)	augmentation from the proposed reservoir at Everton or a 50% reduction in the permanent flood pool at the Guelph reservoir.

When determining upstream flow rates for Kitchener and Galt, increases in the upstream WPCP effluent flow rates, due to projected increases in populations, must be considered. Also, since the Galt WPCP is located below the confluence of the Speed and the Grand Rivers, upstream flow rates for the Galt WPCP include a combination of both river flows.

Table 3 presents the design upstream flow (QRUP) utilized in the modelling studies for each WPCP.

TABLE 3. UPSTREAM FLOWS (QRUP) UTILIZED FOR THE DESIGN CASES

YEAR	DESIGN	WATERLOO		KITCHENER		GUELPH		GALT	
	OPTION	m^3/s	cfs	m^3/s	cfs	m^3/s	cfs	m^3/s	cfs
1979	1	1.1	40	1.4	50.9	0.5	17	3.2	114.7
	2	4.2	150	4.6	160.9	1.8	64	6.4	224.7
	3	8.4	300	8.8	310.9	2.5	88	11.9	421.7
	4	11.2	400	11.6	410.9			14.8	521.7
	5	14.0	500	14.5	510.9			18.3	645.7
	6	16.8	600	17.3	610.9			21.1	745.7
2001M*	1	1.1	40	1.7	61.2	0.5	17	4.4	154.0
	2	4.2	150	4.8	171.2	1.8	64	7.5	264.0
	3	8.4	300	9.1	321.2	2.5	88	13.0	461.0
	4	11.2	400	11.9	421.2			15.9	561.0
	5	14.0	500	14.8	521.2			19.4	685.0
	6	16.8	600	17.6	621.2			22.2	785.0
2031M*	1	1.1	40	2.0	70.6	0.5	17	5.9	206.9
	2	4.2	150	5.1	180.6	1.8	64	9.0	316.9
	3	8.4	300	9.4	330.6	2.5	88	14.5	513.9
	4	11.2	400	12.2	430.6			17.4	613.9
	5	14.0	500	15.0	530.6			20.9	737.9
	6	16.8	600	17.8	630.6			23.7	837.9
2031H*	1	1.1	40	2.1	75.2	0.5	17	6.7	237.4
	2	4.2	150	5.2	185.2	1.8	64	9.8	347.4
	3	8.4	300	9.5	335.2	2.5	88	15.4	544.4
	4	11.2	400	12.3	435.2			18.2	644.4
	5	14.0	500	15.2	535.2			21.7	768.4
	6	16.8	600	18.0	635.2			24.6	868.4

* M and H denote medium and high density population levels, respectively.

3.1.3 Temperature and pH

As stated previously (Section 1.3), total ammonia is present in wastewater effuents in ionized (NH_4^+) and un-ionized (NH_3) forms, the latter form being potentially toxic to fish. The fraction of each form is dependent on pH and temperature according to the equation (Willingham 1976):

$$C_u = \frac{C}{1 + 10^{pKa - pH}}$$

$$pKa = 0.09018 + \frac{2729.92}{273.2 + T^o} \qquad 6)$$

C = concentration of total ammonia

C_u = concentration of un-ionized ammonia

pH = pH of receiving water

pKa = $-\log K_a$, where K_a = dissociation constant for total ammonia

T^o = temperature of receiving water, ^oC

pH values of 7.8 and 8.2, based on observed field data, were utilized for the study. Temperature values used in the model range from 5^oC to 25^oC in 5 degree steps. Lower values of 5^o and 10^oC are considered representative of winter conditions, while the range 15^o - 25^o is representative of late spring, summer and early fall temperature variation experienced in the basin.

3.1.4 Treatment Levels

All the wastewater treatment plants within the study area of the basin, with the exception of the Guelph plant, are currently operating as conventional activated sludge plants. In order to assess the effects of various treatment levels on instream concentrations of chlorine and ammonia within the mixing zones, three treatment levels are examined in the study:

1. Conventional Activated Sludge (CAS): Primary and secondary treatment to remove carbonaceous BOD; effluent disinfection to destroy micro-organisms of public health concern.

2. Tertiary: CAS plant with nitrification to reduce nitrogenous BOD, sand filtration for effluent polishing; and disinfection of effluent.

3. Advanced: Tertiary with activated carbon adsorption (ACA) and effluent disinfection. ACA reduces carbonaceous and nitrogenous BOD, and also tends to remove small amounts of ammonia.

Table 4 presents typical effluent concentrations of total residual chlorine and total ammonia attainable by the three levels of treatment.

TABLE 4: EFFLUENT CHARACTERISTICS FOR VARIOUS WASTEWATER TREATMENT LEVELS

TREATMENT LEVEL	TOTAL RESIDUAL CHLORINE	TOTAL AMMONIA
Conventional Activated Sludge	500 ug/L	12.5 mg/L
Tertiary	500 ug/L	1.5 mg/L
Advanced	500 ug/L	1.0 mg/L

3.1.5 Limited Use Zone Boundary

The publication "Water Management" (MOE, 1978) states that:

> "The mixing zone dimensions will be kept as small as possible while ensuring that the provincial water quality objectives are met at the boundary." It is also stated that "a mixing zone shall not be allowed to create a barrier to the migration of fish and aquatic life."

Therefore, the specified instream water quality objective, C_s, must be met at an acceptable lateral boundary of the LUZ, q_L, to ensure an adequate zone of passage for aquatic biota.

In order to examine the sensitivity of the lateral boundary of LUZ on the allowable effluent concentration and maximum longitudinal spread, model runs were made with q_L ranging from 20% to 40% of the total river flow, Q. Based on preliminary analyses and discussion with Grand River Water Quality Sub-Committee members, a LUZ of 40% of the total river flow was considered appropriate for the Grand River Basin. Consequently, the remaining 60% of the total river flow represents the zone of passage. (Note: All model runs include predictions of allowable effluent concentrations and maximum longitudinal spreads with $p_L = 0.2$, 0.3 and 0.4, where $p_L = q_L/Q$).

3.1.6 Instream Process Parameters

The instream process parameters required as model inputs are: (i) streamflow, channel width, mean depth and mean velocity at known distances in each river stretch below the outfalls, as well as the empirical constants of the Leopold-Maddock equations; (ii) the dimensionless coefficient, B'; and (iii) first-order decay rate coefficients of TRC and total ammonia. The hydraulic parameters including the coefficient, B', were obtained from field surveys carried out at each of the study locations during 1975. The decay rates of TRC were based on the values determined from field data analyses in other streams and rivers (Gowda 1978 and 1980a). The ammonia decay rates were obtained from the results of previous waste assimilation studies. As stated earlier, the instream process parameters were scaled up to account for changes in streamflow and temperature values. Instream process parameters utilized for this study can be found in the Appendix.

The general procedures involved in field data collection, parameter estimation and scale-up of various parameters were described in another publication (Gowda 1980b), which should be consulted for details.

3.2 Modelling Results

Figures 5 through 14 illustrate the results of the model runs for total residual chlorine and un-ionized ammonia for the mixing zones below the Waterloo, Kitchener, Guelph and Galt wastewater treatment plants. As stated previously, the stream tube model was not applied to the Brantford case. Results of runs with temperatures of $5^{o}C$ and $25^{o}C$ are presented on the figures to show the effects of two temperature extremes. Although two pH options were utilized for ammonia, the predictions with pH = 8.2 are represented on the figures, since the concentration of un-ionized ammonia is greater at a higher pH, when all other parameters are held constant.

A temperature of $5^{o}C$ is considered representative of winter conditions; therefore, plots of runs at $5^{o}C$ are presented with the corresponding winter discharges on the Grand River of 1.1 m^3/sec (40 cfs) and 4.2 m^3/sec (150 cfs) at Bridgeport. Plots of predictions with a temperature of $25^{o}C$ and upstream flows at Bridgeport of 8.4 m^3/sec (300 cfs) to 16.8 m^3/sec (600 cfs) are considered to be representative of summer conditions. For the Speed River, the combination of $5^{o}C$ and 0.5 m^3/sec (17 cfs) represent winter conditions, and $25^{o}C$ and 1.8 m^3/sec (64 cfs) and 25 m^3/sec (88 cfs) represent summer conditions. Since present and future water quality is dependent on changes in effluent loading rates, the total pollutant load given by the product $Q_e . C_e$ (effluent flow rate x effluent concentration) expressed in milligrams per second, is plotted against instream critical concentration, C_L, in Figures 5 to 14. The figures show increasing load through time at constant flow (x-axis) and the resultant critical concentration (maximum at LUZ boundary) achieved in the stream (y-axis). Several design upstream flow conditions are shown for each case.

In order to maintain a zone of passage which is the portion of the channel containing 60% of the total river flow, the critical concentration, C_L, of the pollutant must not exceed the specified instream water quality guideline, C_S, at a LUZ boundary of 40% of the total river flow, as previously stated. Therefore, portions of the curves extending above C_S are indicative of conditions where a 60% zone of passage is not attainable.

The following subsections describe the results of model predictions at each location. For those conditions where the PWQO objectives are not met, allowable effluent concentrations which would result in compliance with the PWQO have been calculated. The results are summarized in Tables 5, 6 and 7 for the Waterloo, Kitchener and Guelph cases, respectively. Downstream shoreline distances (X_{sceA}), where the PWQO for un-ionized ammonia is met have also been calculated; the results are presented in Table 8. Generally, the smaller values of X_{sceA} are associated with higher temperature and lower streamflow rates. The values of X_{sceA} where the PWQO for total residual chlorine is met, were generally small (in comparison with those for un-ionized ammonia) and are not presented in this report.

In Figures 5 to 14, the instream critical concentrations of TRC for a 40% lateral boundary of LUZ are seen to increase with an increase in streamflow, whereas the critical concentrations of ammonia decrease with an increase in the streamflow. An examination of the various TRC modelling runs indicates that the critical concentration of TRC increases with streamflow up to some value and then declines. The reasons for such predictions are not clear; however, different combinations of hydraulic parameters and decay rates have been shown to result in such predictions (Gowda 1978; 1980a).

3.2.1 Waterloo

Figure 5 illustrates the results of the model runs for total residual chlorine for the mixing zone in the Grand River below the Waterloo WPCP. The curves do not extend above the PWQO of 2 ug/L for TRC, indicating compliance with respect to chlorine toxicity during both winter and summer conditions.

Figure 6 shows the plots for un-ionized ammonia with the Waterloo WPCP operating at the CAS level of treatment. The PWQO of 0.02 ug/L for un-ionized ammonia is exceeded under virtually all conditions of loading and temperature. The addition of tertiary treatment (in-plant nitrification) at the Waterloo WPCP would result in un-ionized ammonia concentrations for both winter and summer conditions being within the PWQO (Fig. 7).

For conditions where the PWQO for un-ionized ammonia are not in compliance, the allowable effluent total ammonia concentrations, C_{eA}, necessary to limit the lateral boundary of the LUZ to 40%, were calculated according to Equation 1. The results, presented in Table 5, show that except for upstream flows greater than 14.2 m^3/s (500 cfs) under the 1979 population conditions, the values of allowable effluent total ammonia concentrations are generally smaller than 12.5 mg/L (the nominal total ammonia in a CAS treatment plant). These results indicate that tertiary treatment (nitrification) is required at the Waterloo WPCP.

The values of X_{sceA} for total ammonia, presented in Table 8, show that the shoreline distances at which the PWQO is met would be significantly smaller with tertiary treatment at the Waterloo WPCP, in comparison to those attainable with the CAS treatment level.

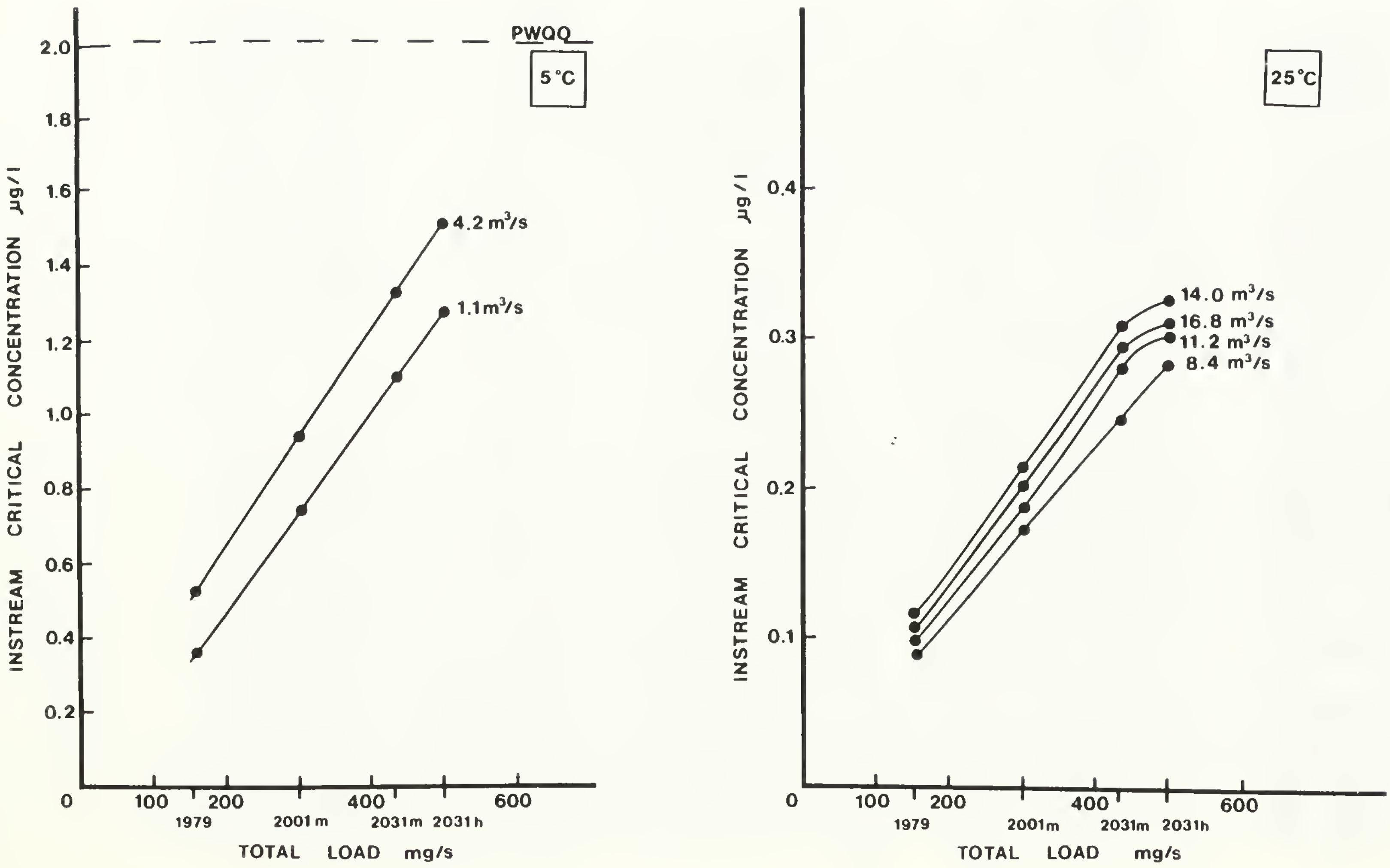


Figure 5. Critical concentrations of total residual chlorine for the Waterloo WPCP.

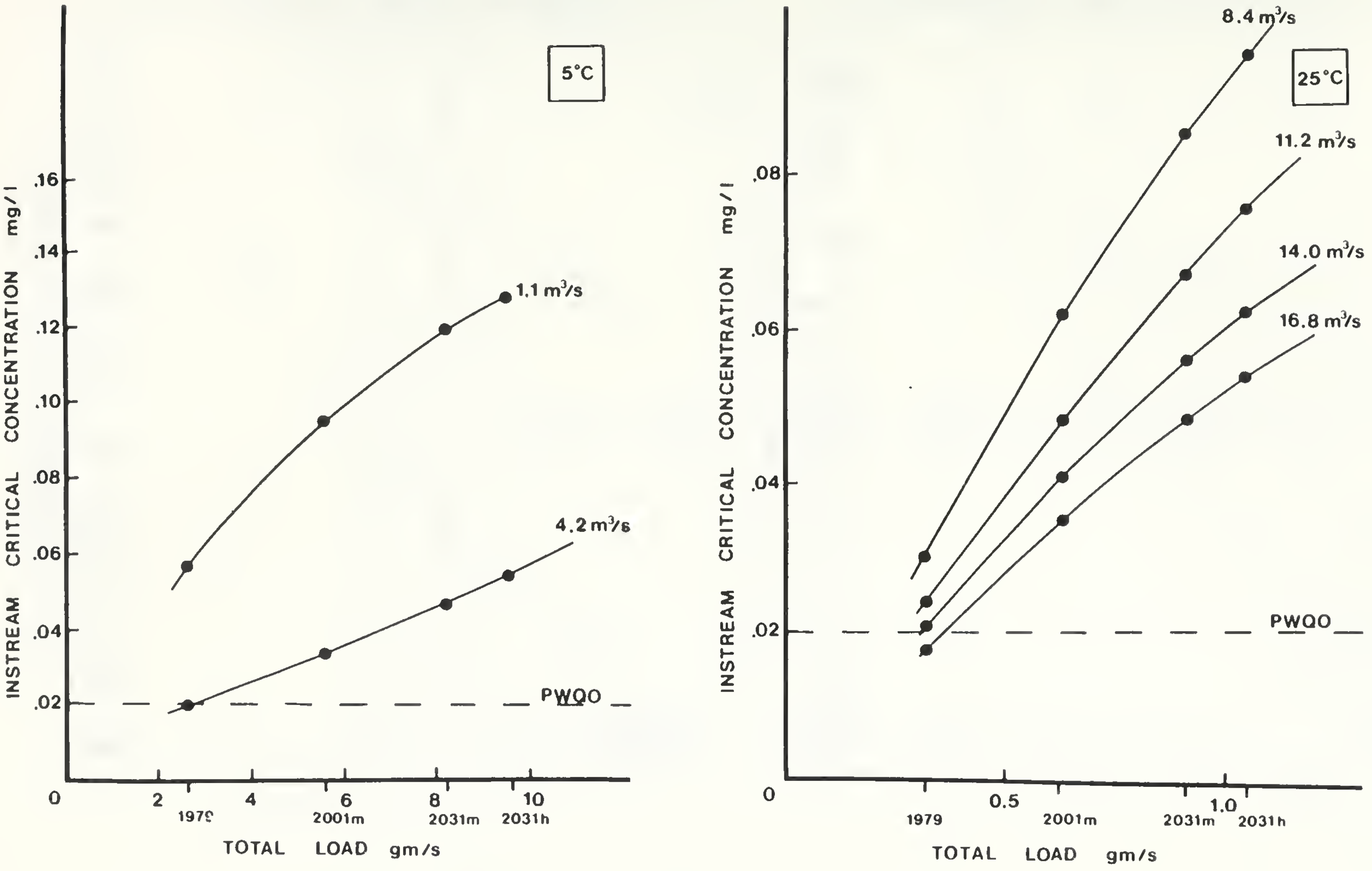


Figure 6. Critical Concentrations of Un-ionized Ammonia with CAS Treatment at the Waterloo WPCP.

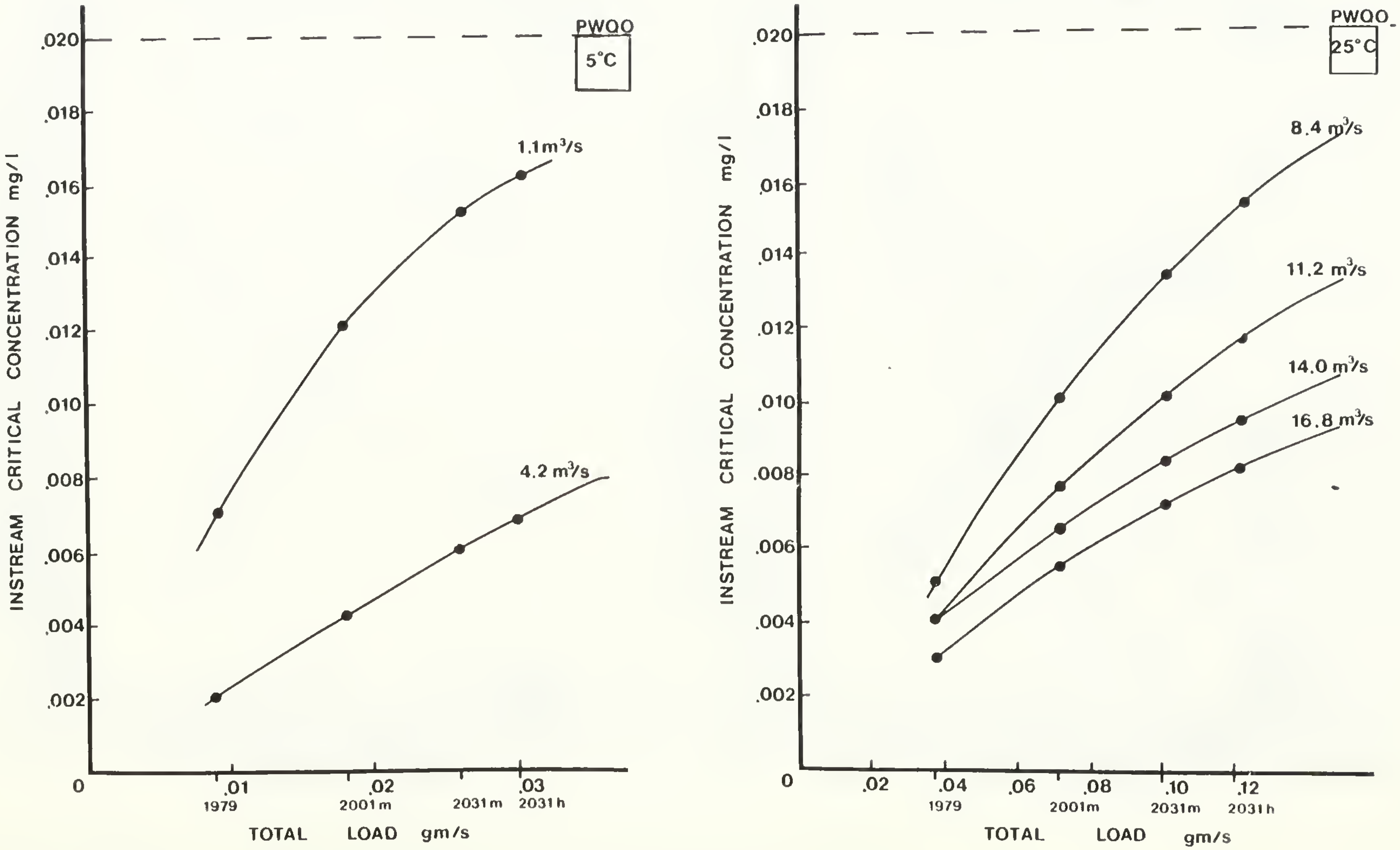


Figure 7. Critical Concentrations of Un-ionized Ammonia with Tertiary Treatment at the Waterloo WPCP.

TABLE 5: ALLOWABLE EFFLUENT CONCENTRATIONS* OF TOTAL AMMONIA AT THE WATERLOO WPCP TO MAINTAIN A 40% LIMITED USE ZONE

Upstream Flow m^3/s	Upstream Flow cfs	Temperature °C	Year	Allowable Effluent Concentration to Meet PWQO Targets mg/L (as N)
1.1	40	5	1979	4.39
			2001M	2.69
			2031M	2.14
			2031H	1.98
4.2	150	5	2001M	7.30
			2031M	5.33
			2031H	4.75
8.5	300	25	1979	7.67
			2001M	4.05
			2031M	2.88
			2031H	2.54
11.3	400	25	1979	9.97
			2001M	5.22
			2031M	3.69
			2031H	3.24
14.2	500	25	1979	12.24
			2001M	6.39
			2031M	5.22
			2031H	3.94
17.0	600	25	2001M	7.43
			2031M	5.22
			2031H	4.57

* The effluent concentration of total ammonia at Waterloo is presently 12.5 mg/L. Allowable effluent concentrations are those required (i.e. less than 12.5 mg/L) to achieve PWQO targets.

3.2.2 Kitchener

The modelling results for total residual chlorine indicate that a zone of passage which is 60% of the total river flow in the Grand River downstream of the Kitchener wastewater treatment plant is achievable for all design case population levels, upstream flows and temperatures (Figure 8).

Figure 9 shows noncompliance of the PWQO for un-ionized ammonia for 1979 winter and summer conditions, with Kitchener operating at conventional treatment. When tertiary treatment at the Kitchener WPCP is simulated, the PWQO are in noncompliance only during the summer conditions at 8.4 m^3/sec (300 cfs) after approximately 2001 and by 2031H for 11.2 m^3 sec (400 cfs), as seen in Figure 10. With ACA treatment at Kitchener, the results presented in Figure 11 show that the PWQO for un-ionized ammonia is met under all the design cases.

Table 6 summarizes the allowable effluent concentrations of total ammonia necessary to achieve the PWQO for ammonia; the values range from 1.28 to 7.11 mg/L. The results indicate the need for inplant nitrification at the Kitchener WPCP under the 1979 design condition.

For total ammonia, the range of X_{sceA} is 11 to 11,650 meters and greater with CAS treatment, 650 to 14,100 meters with tertiary treatment and 325 to 6,750 meters with ACA treatment (Table 8).

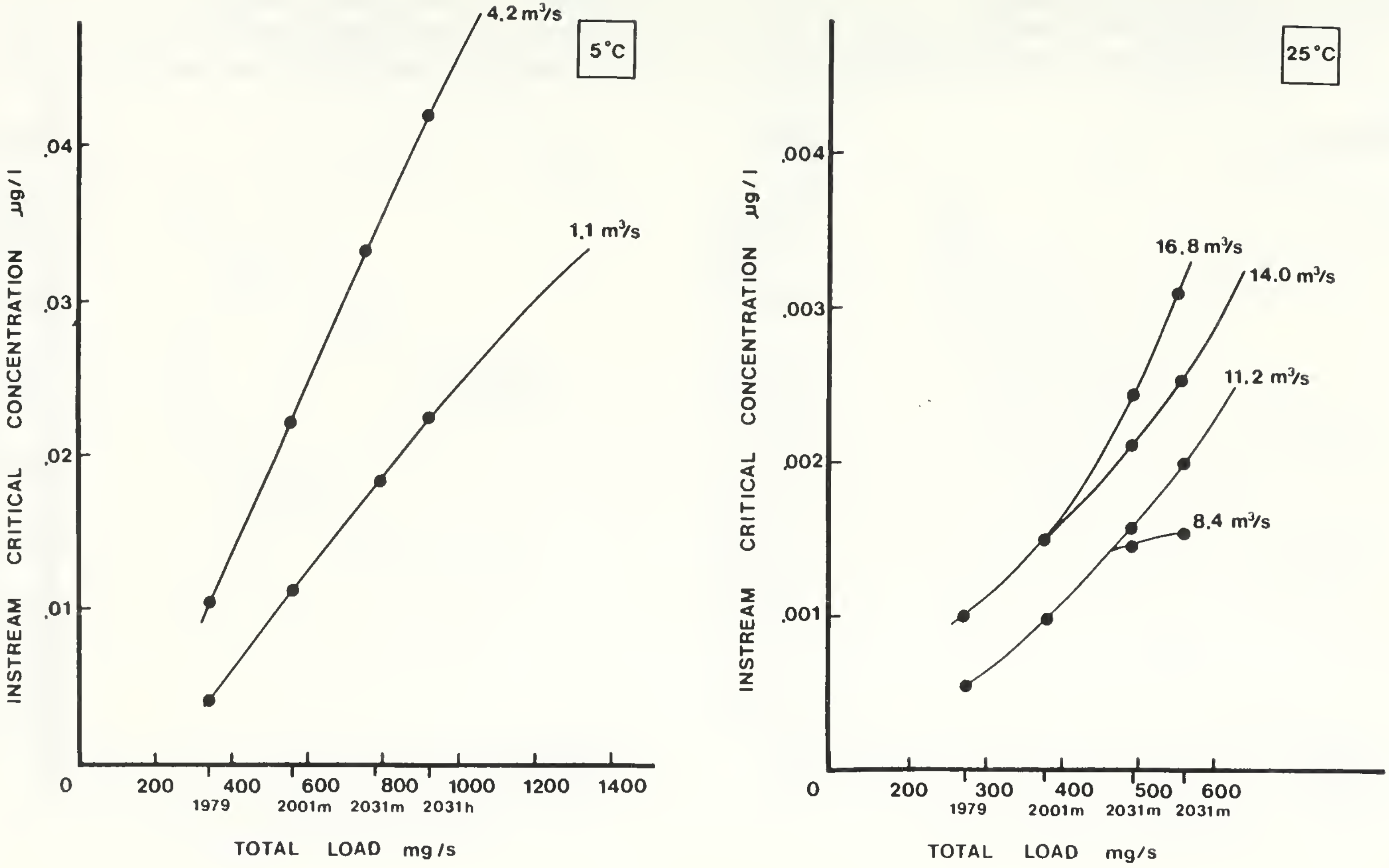


Figure 8. Critical concentrations of total residual chlorine at the Kitchener WPCP.

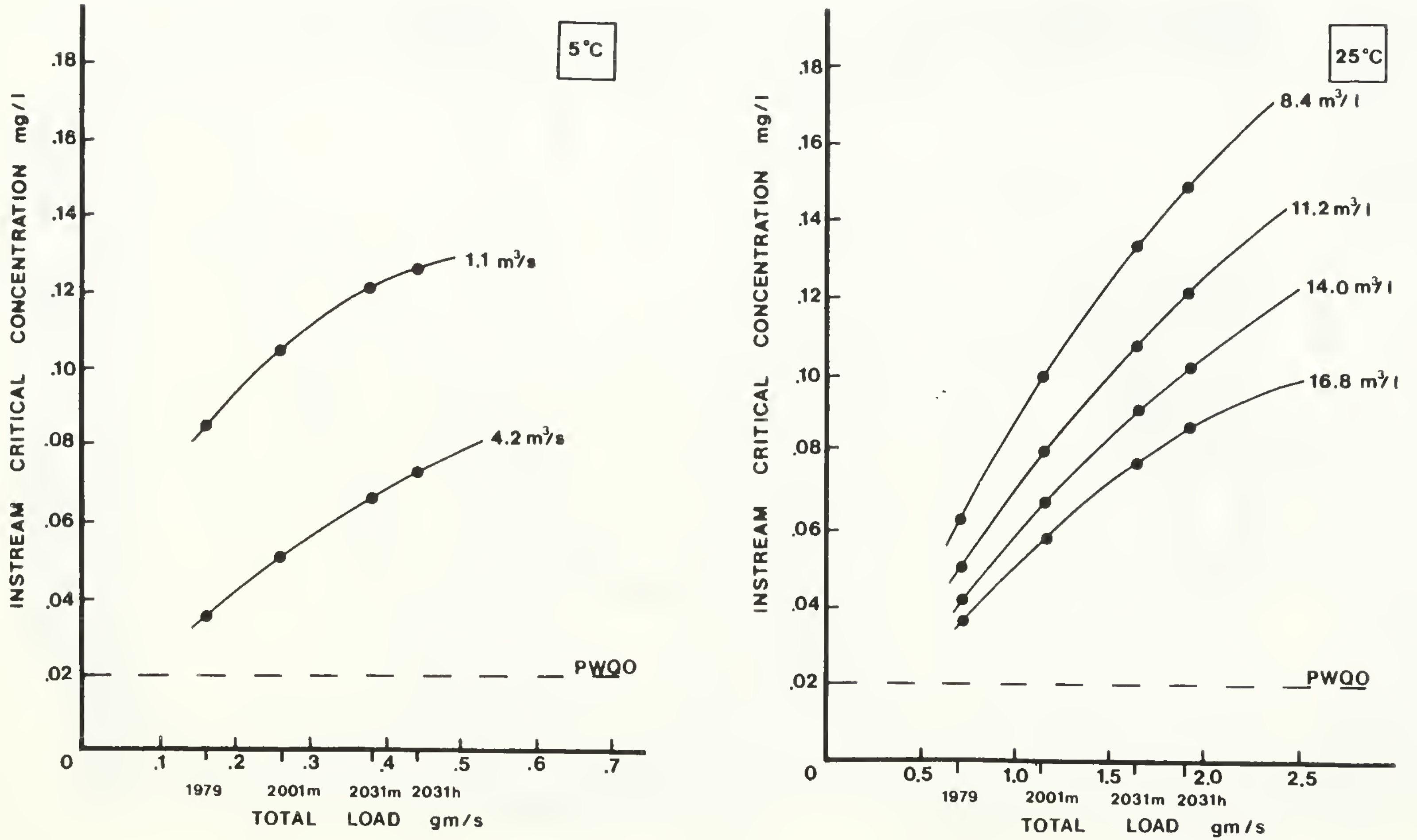


Figure 9. Critical Concentrations of Un-ionized Ammonia with CAS Treatment at the Kitchener WPCP.

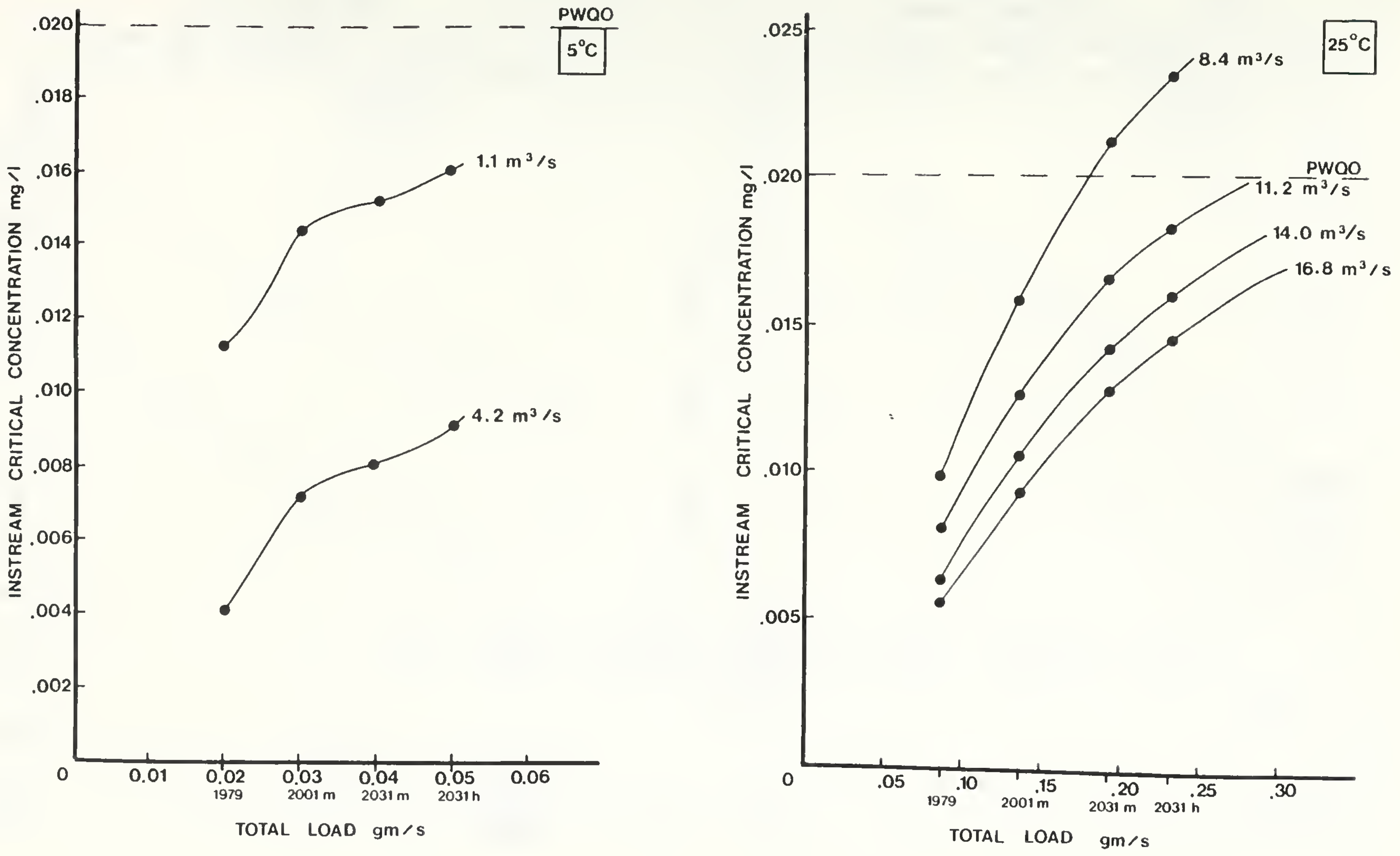


Figure 10. Critical Concentrations of Un-ionized Ammonia with Tertiary Treatment at the Kitchener WPCP.

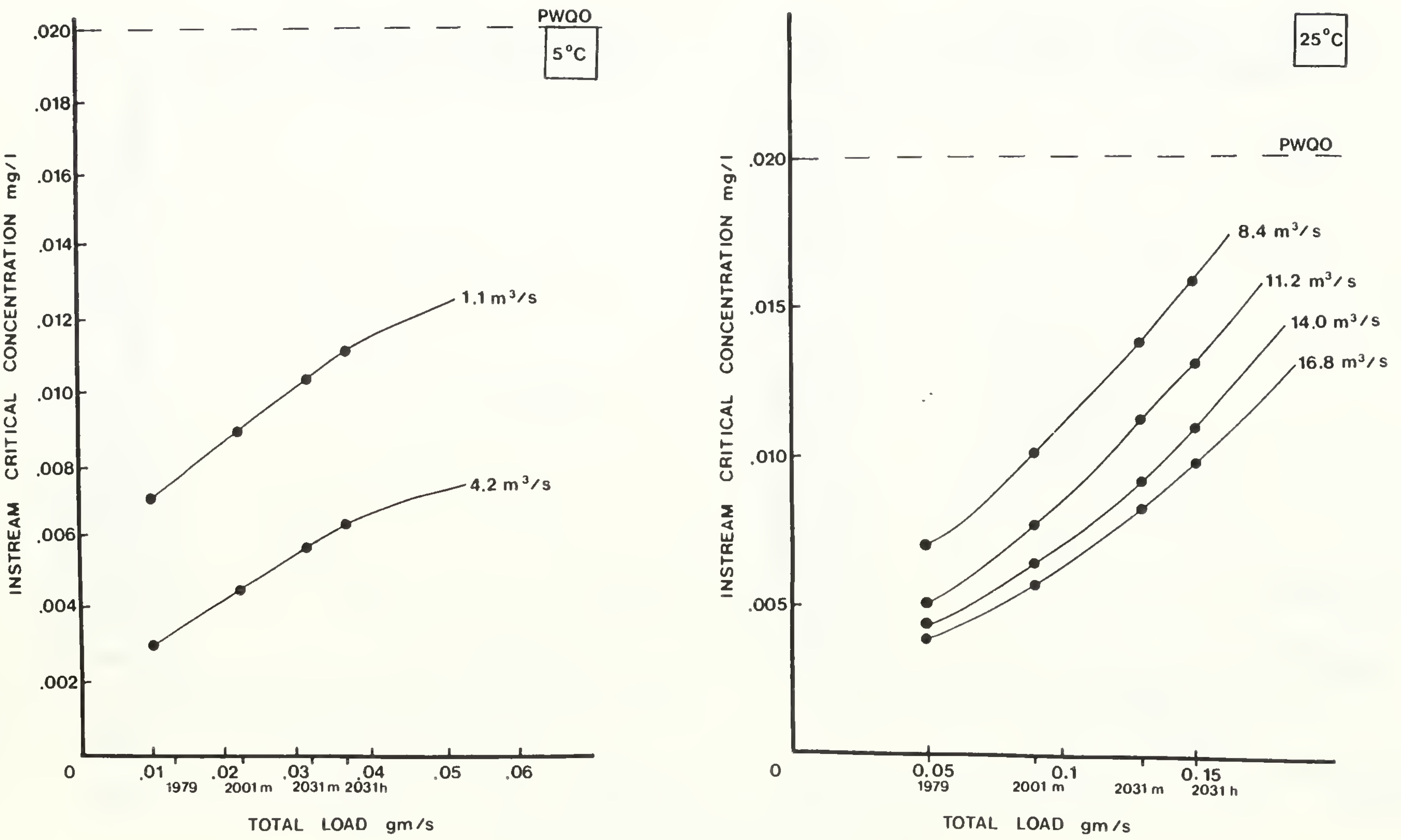


Figure 11. Critical Concentrations of Un-ionized Ammonia with ACA Treatment at the Kitchener WPCP.

TABLE 6. ALLOWABLE EFFLUENT CONCENTRATIONS OF TOTAL AMMONIA AT THE KITCHENER WPCP TO MAINTAIN A 40% LIMITED USE ZONE

Treatment Level	Present Effluent Concentration	Upstream Flow m^3/sec	Upstream Flow cfs	Temperature °C	Year	Allowable Effluent Concentration to Meet PWQO Target mg/L (as N)
Conventional Activated Sludge	12.5 mg/L total ammonia	1.1	40	5	1979	2.95
					2001M	2.38
					2031M	2.08
					2031H	1.98
		4.2	150	5	1979	7.11
					2001M	4.87
					2031M	3.82
					2031H	3.48
		8.5	300	25	1979	3.96
					2001M	2.56
					2031M	1.90
					2031H	1.69
		11.3	400	25	1979	5.01
					2001M	3.18
					2031M	2.34
					2031H	2.07
		14.2	500	25	1979	6.03
					2001M	3.80
					2031M	2.76
					2031H	2.44
		17.0	600	25	1979	7.04
					2001M	4.41
					2031M	3.19
					2031H	2.81
Tertiary	1.5 mg/L total ammonia	8.5	300	25	2031M	1.43
					2031H	1.28

3.2.3 Guelph

There are no problems in attaining a 60% zone of passage with regard to total residual chlorine in the Speed River below the Guelph wastewater treatment plant (Figure 12) under summer high flow conditions. Only after the 2001M projected population level at Guelph, under low flow winter conditions, are the PWQO violated.

With the addition of tertiary treatment (nitrification) at Guelph, the PWQO for ammonia is violated in 1979 under summer conditions with the current population and by 2001M, for winter conditions (Figure 13).

The X_{sceA} values are in the range of 4025-8200 meters with regard to ammonia under tertiary treatment conditions (see Table 8).

The allowable effluent concentration of total ammonia and chlorine under various design conditions, have been presented in Table 7. In the case of total ammonia, the values of C_{eA} are lower than 1.5 mg/L indicating a need for further reduction in effluent ammonia concentrations (through advanced treatment methods). In order to meet the PWQO for residual chlorine, dechlorination of effluent by the year 2031 is also indicated by the results (for chlorine) presented in Table 7.

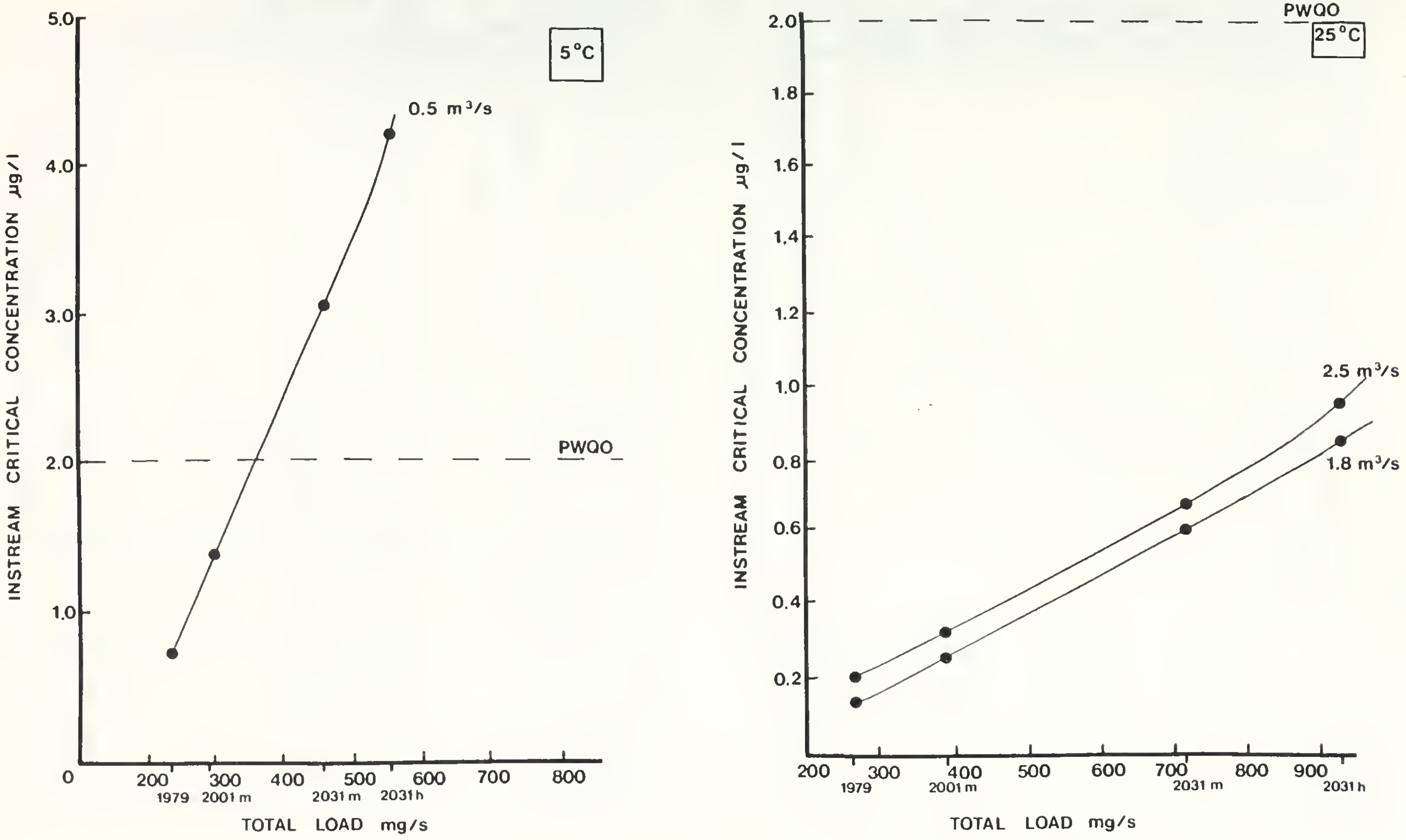


Figure 12. Critical concentrations of total residual chlorine for the Guelph WPCP.

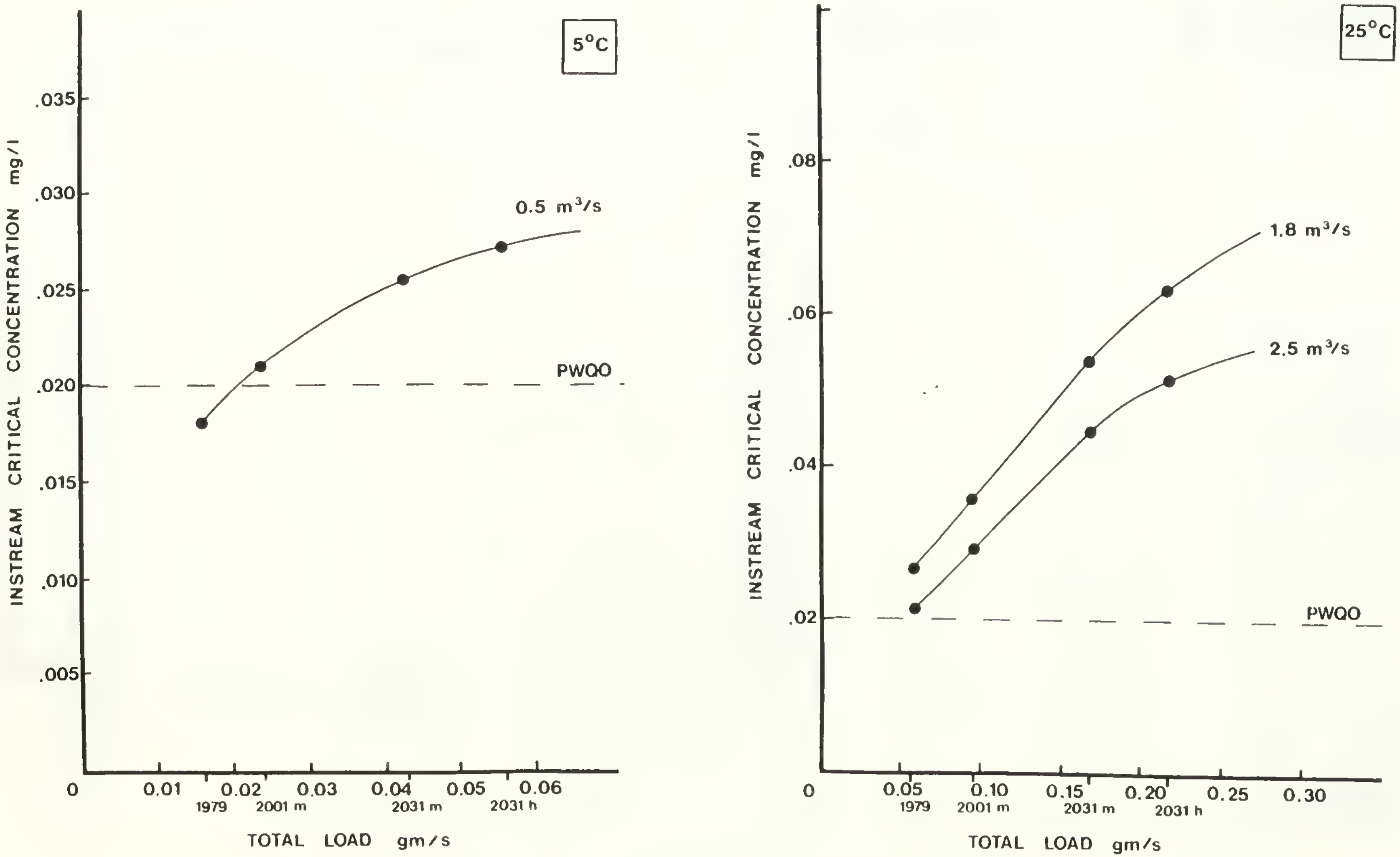


Figure 13. Critical Concentrations of Un-ionized Ammonia with Tertiary Treatment at the Guelph WPCP.

TABLE 7. ALLOWABLE EFFLUENT CONCENTRATIONS OF TOTAL AMMONIA AND CHLORINE AT THE GUELPH WPCP NECESSARY TO MAINTAIN A 40% LUZ

Treatment Level	Present Effluent Concentration	Upstream Flow m^3/sec	Upstream Flow cfs	Temperature ^oC	Year	Allowable Effluent Concentration to Meet PWQO Target mg/L
Tertiary	1.5 mg/L total ammonia	0.5	17	5	2001M	1.45
					2031M	1.20
					2031H	1.12
		1.8	64	25	1979	1.13
					2001M	0.82
					2031M	0.56
					2031H	0.48
		2.5	88	25	1979	1.43
					2001M	1.02
					2031M	0.66
					2031H	0.56
Dechlorination	500 ug/L	0.5	17	5	2031M	338.75 (ug/l)
					2031H	235.50 (ug/l)

3.2.4 Galt

A 60% zone of passage in the Grand River below the Galt WPCP is attainable with regard to total residual chlorine. A chlorine concentration of 500 ug/l in the effluent does not result in the LUZ being extended to 40% of the total river flow, so no plot of the results has been presented.

Critical instream concentrations of ammonia are below the PWQO for all the design conditions (Fig. 15). Results presented in Table 8 show that the values of X_{sceA} for ammonia are 15,100 meters and greater for CAS treatment conditions at the Galt WPCP.

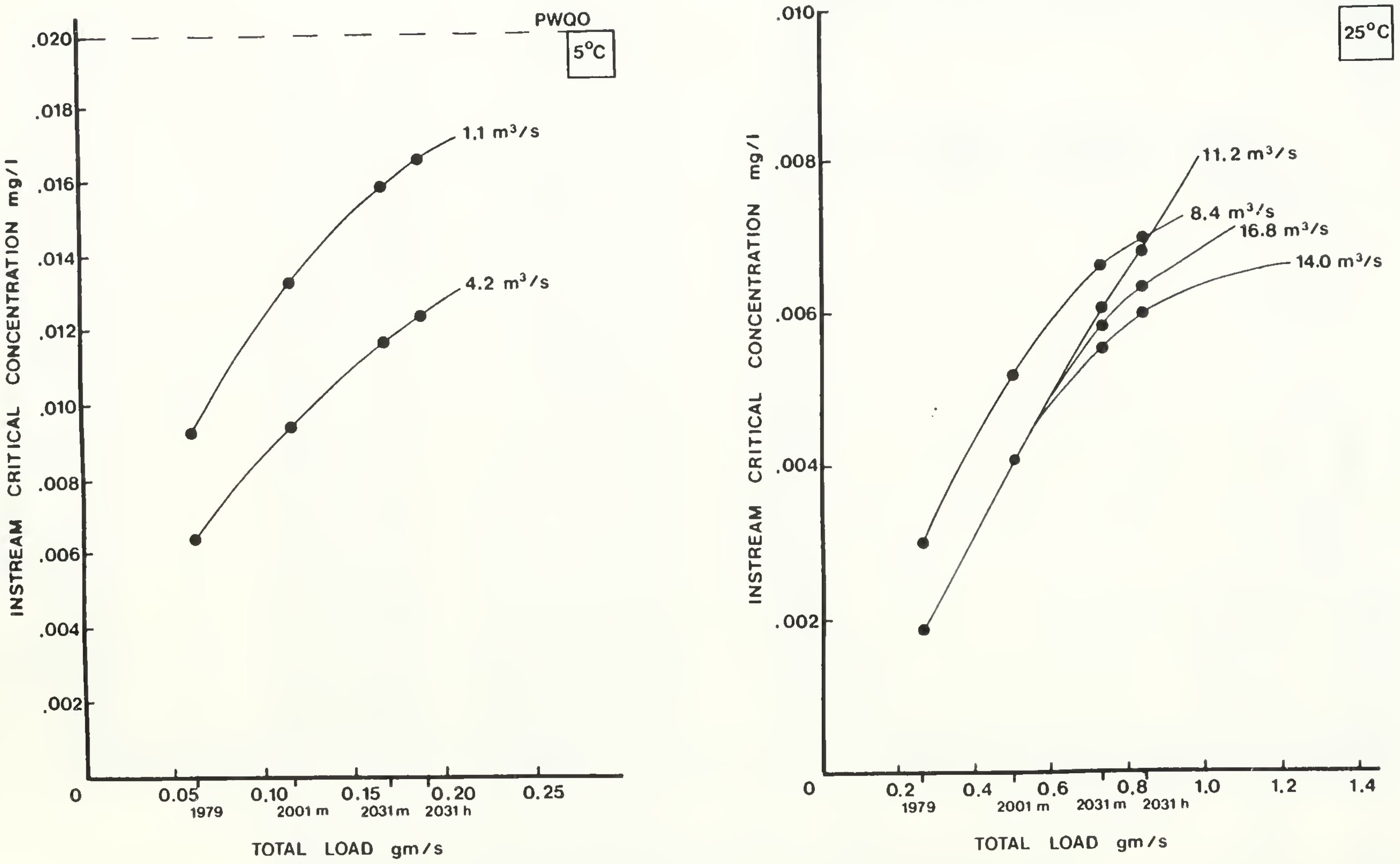


Figure 14. Critical Concentrations of Un-ionized Ammonia with Tertiary Treatment at the Galt WPCP.

TABLE 8. SHORELINE DISTANCES DOWNSTREAM OF OUTFALLS WHERE THE PWQO FOR UNIONIZED AMMONIA IS MET

Sewage Treatment Plant	Temperature (^{o}C)	Streamflow at Bridgeport (cfs)	Distance Downstream of Outfall(m)			
			1979	2001M	2031M	2031H
Waterloo (CAS)	5	40	*	*	*	*
		150	10048	*	*	*
	25	300	11448	17548	*	*
		400	9948	16298	20448	*
		500	8648	15048	19348	*
		600	7548	13898	18248	20098
Waterloo (Tertiary)	5	40	2082	4698	7384	8548
		150	70	222	477	1782
	25	300	427	3340	6148	7748
		400	172	2282	2848	4898
		500	120	1532	2690	3440
		600		364	2182	2490
Kitchener (CAS)	5	40	*	*	*	*
		150	*	*	*	*
	25	300	14250	*	*	*
		400	13350	*	*	*
		500	12500	*	*	*
		600	11650	*	*	*
Kitchener (Tertiary)	5	40	3300	5000	6500	7150
		150	650	1350	2000	2350
	25	300	3050	6750	11350	14100
		400	1900	4400	7700	9550
		500	1350	3100	5600	7000
		600	1050	2300	4250	5350
Kitchener (Advanced)	5	40	1600	2250	2950	3250
		150	325	650	1000	1100
	25	300	1600	3200	5500	6750
		400	950	2050	3700	4600
		500	650	1600	2600	3300
		600	500	1100	1950	2500
Guelph (Tertiary)	5	17	4025	5100	7150	8200
	25	64	5050	4425	6050	6900
		88	4200	4075	5800	6650
Galt (CAS)	5	40	39850	*	*	*
		150	26750	43700	*	*
	25	300	17200	22850	26550	27700
		400	16600	22650	26500	27700
		500	15800	22200	26300	27500
		600	15100	21750	26000	27250

* The predicted distance, X_{sceA} exceeds the distance to the next downstream water pollution control plant.

3.2.5 Brantford

As stated elsewhere in this report, the two dimensional stream tube model was not applied to the Brantford WPCP as the effluent mixes completely across the river in a short distance below the outfall. Therefore, concentrations of un-ionized ammonia and chlorine immediately below the outfall were predicted based on the instantaneous completely mixed assumption (ICM) according to:

$$C_a = \frac{(C_e)(Q_e)}{Q_r} \tag{7}$$

C_a = completely mixed concentration of pollutant in river just below outfall.

C_e = concentration of pollutant in effluent.

Q_e = effluent flow rate.

Q_r = total river flow rate, given by the sum of upstream and effluent flow rates.

Concentrations of ammonia and chlorine immediately below the outfall of the Brantford WPCP, under various design conditions, are presented in Tables 9 and 10. For each design case, the downstream distance, X_s, at which the pollutant concentration is equal to the PWQO, was calculated from the relationships:

$$C_{st} = C_a \exp\left(-K\, X_s/u_{av}\right) \tag{8}$$

$$X_s = \frac{U_{av} \log_e}{K} \left(\frac{C_a}{C_{st}}\right) \tag{9}$$

where

C_{st} = the desired instream completely mixed concentration (mg/L)

C_a = the instantaneous, completely mixed concentration immediately below the outfall (mg/L)

X_s = downstream distance from the outfall where the concentration is C_{st} (m)

K = decay rate coefficient (sec^{-1}, base e)

U_{av} = average stream velocity (m/s)

TABLE 9: CONCENTRATIONS OF TOTAL RESIDUAL CHLORINE BASED ON INSTANTANEOUS COMPLETELY MIXED ASSUMPTION AND DISTANCES WHERE PWQO TARGET IS MET FOR THE BRANTFORD WPCP WITH C_e = 500 ug/L

Population	Season	Upstream Design* Case Flows		Instantaneous Completely Mixed Concentration of TRC (ug/L)	Downstream Distance Where PWQO Target is Met (m)
		m^3/sec	cfs		
1979	Winter	13.8	486.0	17.0	11.6
		16.6	586.0	14.0	10.5
	Summer	20.5	726.0	12.0	9.7
		23.4	826.0	10.0	8.7
2001M	Winter	15.1	535.0	22.0	13.0
		18.0	635.0	19.0	12.2
	Summer	22.0	775.0	15.0	10.9
		24.8	875.0	13.0	8.7
2031M	Winter	16.9	596.0	30.0	14.6
		19.7	696.0	25.0	13.6
	Summer	23.7	836.0	21.0	12.7
		26.5	936.0	19.0	12.2
2031M	Winter	17.3	611.0	40.0	16.2
		20.1	711.0	31.0	14.8
	Summer	24.1	851.0	26.0	13.9
		26.9	951.0	23.0	13.2

* Upstream flows at Brantford are a combination of flows from the main Grand, Speed and Nith Rivers.

TABLE 10: CONCENTRATIONS OF AMMONIA BASED ON ICM AND DISTANCES WHERE PWQO TARGET IS MET FOR THE BRANTFORD WPCP WITH C_e = 12.5 mg/L.

Population	Season	Upstream Flow at Bridgeport		Instantaneous Completely Mixed Concentration of TRC (ug/L)	Downstream Dista Where PWQO Targ is Met (m)
		m^3/sec	cfs		
1979	Winter	13.8	486.0	0.43	991
		16.6	586.0	0.36	685
	Summer	20.5	726.0	0.29	312
		23.4	826.0	0.26	124
2001M	Winter	15.1	535.0	0.55	1409
		18.0	635.0	0.46	1126
	Summer	22.0	775.0	0.38	778
		24.8	875.0	0.34	586
2031M	Winter	16.9	596.0	0.74	1927
		19.7	696.0	0.64	1669
	Summer	23.7	836.0	0.53	1351
		26.5	936.0	0.48	1181
2031M	Winter	17.3	611.0	0.89	2239
		20.1	711.0	0.77	1996
	Summer	24.1	851.0	0.65	1703
		26.9	951.0	0.58	1507

*Based on a pH of 8.2 and a temperature of 5°C (winter) and 25°C (summer).

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The results based on the instantaneous completely mixed assumption indicate that the PWQO in the Grand River below the Brantford WPCP outfall would be met within very small distances in the case of TRC and distances ranging up to 2239 meters for un-ionized ammonia.

It can be noted from a previous study on the Brantford WPCP by Wisz et al (1978), the total residual chlorine in the effluent averaged 1399 ug/L. Residual chlorine was observed at approximately 600 m downstream of the outfall and that some lateral variability in the TRC concentrations occurred. Based on a comparison of this field data with the predictions presented in Table 9, it appears that the decay rate used in the instantaneous complete mixing calculations was somewhat high. However, for the sake of consistency, the same decay rate has been used in all five Grand River studies presented in this report.

3.3 Assumptions and Limitations of the Model

The model used in this study is applicable only to steady state conditions.

A major assumption of the model is that no significant background concentration of the pollutant occurs. The model only considers the effect of pollutant concentration in the effluent released from the wastewater treatment plant under consideration.

Decay rates associated with total residual chlorine can be highly variable from one location to another. Previous studies (Gowda, 1980a) have found TRC decay rates in streams to lie in the range of 0.56×10^{-4} to 73×10^{-4} per second at 20°C (to base e). Since TRC decay rates were not measured at each site considered in this study, the decay rate used in the model was an average of these observed extreme rates. Results of a sensitivity analysis on the chlorine decay rates at the Waterloo WPCP indicated that with the low TRC decay rate, the PWQO for chlorine is violated in 1979 (300 cfs, 25°C). With the higher decay rate, no violations occurred. Therefore, a more detailed examination of chlorine decay rates within the basin should be undertaken.

As stated previously, the Kitchener WPCP outfall is located at the mid-point of the river. Since the model is based on a bank outfall, the outfall for the Kitchener plant has been considered to be moved to a different location for modelling purposes. More thorough studies would have to be conducted to determine if an improvement in effluent quality would alleviate the problem of the effluent barrier which occurs with the current discharge location.

Due to data limitations and time and resource constraints, the model was validated for a conservative material for the Waterloo site only. Therefore, the results presented in this report should be considered to be indicative only of general, relative trends in water quality changes resulting from various management options.

More detailed descriptions of model assumptions are given in Water Resources Paper #14 (Gowda, 1980b).

IV SUMMARY

Results of application of the mixing zone model indicate that within the Grand River basin, for the design cases considered, a zone of passage consisting of 60% of the total river flow is attainable with regard to chlorine toxicity. Only beyond the year 2001 projected population level at Guelph, under winter conditions, are the PWQO for chlorine violated outside the mixing zone.

In order to maintain the 0.02 mg/L objective for un-ionized ammonia, at the boundary of the mixing zone, tertiary treatment is necessary at the Waterloo wastewater treatment plant. With implementation of tertiary treatment at Kitchener, Provincial Objectives for un-ionized ammonia can be achieved until 2031 (summer low flow); and with the subsequent addition of advanced treatment (ACA), no violations of the objective would occur. The current tertiary treatment level at the Guelph wastewater treatment plant is not sufficient to achieve the 0.02 mg/L objective under summer low flow conditions. At Galt, no additional treatment over conventional activated sludge is necessary to comply with the PWQO for un-ionized ammonia.

Due to complete cross-sectional mixing of effluent in the river in a short distance below the outfall, the two dimensional mixing zone model was not applied to the Brantford case. However, results based on the instantaneous complete mixing assumption indicate that residual chlorine concentrations may exceed the PWQO for approximately 20 m downstream and un-ionized ammonia concentrations may exceed objectives for 124 to 2239 m below the outfall, depending on the design conditions.

Given the limitations previously identified, the predicted results should be considered to be indications of water quality changes due to various management options. Detailed field and modelling studies at appropriate implementation stages are recommended, in order to update the results presented in this report.

REFERENCES

Chamberlain, A.J., T. Keller and D. Maraldo (1980). "Water Quality Requirements for Sport Fishes of the Grand River Watershed: A Literature Review", Grand River Basin Water Management Study Technical Report #13, Ontario Ministry of the Environment, Toronto, 111 p.

Eckenfelder, Jr., W.W. (1970). Water Quality Engineering for Practicing Engineers, Barnes and Noble, Inc., New York, 328 p.

EPA (1976). "Quality Criteria for Water", U.S. Environmental Protection Agency, Washington, D.C., 256 p.

Gowda, T.P.H. (1978). "Prediction of Chlorine Residuals in Streams Receiving Sewage Effluent", Water Resources Paper #10, Water Resources Branch, Ontario Ministry of the Environment, Toronto, Canada, 43 p.

Gowda, T.P.H. (1980a). "Critical Concentrations of Unionized Ammonia and Chlorine in Mixing Zones of Rivers", Water Pollution Research Journal of Canada, Vol. 15, No. 3, pp. 255-270.

Gowda, T.P.H. (1980b). "Stream Tube Model for Water Quality Prediction in Mixing Zones of Shallow Rivers", Water Resources Paper #14, Water Resources Branch, Ontario Ministry of the Environment, Toronto, Canada, 141 p.

Ministry of the Environment (1978). "Water Management - Goals, Policies, Objectives and Implementation Procedures of the Ministry of the Environment", Toronto, Ontario, Canada, 67 p.

Smith, A.F. (1981) "Project Investigation Report". Grand River Basin Water Management Study. Technical Report #32 (Draft).

Willson, K.E., A. Kwong, D.G. Weatherbe, L. Post (1981) "Water Quality Simulation Models and Modelling Strategy for the Grand River Basin". Grand River Technical Report #30, Ontario Ministry of the Environment, Toronto (Draft).

Wisz, S., J.D. Ellis, and C. Inniss (1978), "Extent, Magnitude and Decay Rates of Total Residual Chlorine in Sewage Effluent Receiving Streams", Chlorination Committee Technical Report No. 2, Ministry of the Environment, Toronto, Ontario, 43 p.

Willingham, W.T. (1976). "Ammonia Toxicity", Control Technology Branch, Water Division, U.S. Environmental Protection Agency, Region VIII, 19 p.

Yotsukura, N. (1977). "Derivation of Solute-Transport Equations for a Turbulent Natural-Channel Flow", Journal of Research, U.S. Geological Survey, Vol. 5, No. 3, pp 277-284.

Yotsukura, N. and E. Cobb (1972). "Transverse Diffusion of Solutes in Natural Streams", U.S. Geological Survey Professional paper 582-C, U.S. Government Printing Office, Washington, D.C., 19 p.

Yotsukura, N. and W. Sayre (1976). "Transverse Mixing in Natural Channels", Water Resources Research, Vol. 12, No. 4, pp 695-704.

APPENDIX

A-1 LIST OF MIXAPPLN PROGRAM

```
C      PROGRAM NAME   MIXAPPLN  * * STREAMTUBE MODEL FOR PIPE OUTFALL
C     THIS PROGRAM IS SET UP FOR CONSERVATIVE, NONCONSERVATIVE WITH
C     FIRST ORDER DECAY(VIZ.,RESIDUAL CHLORINE, PHENOL, RADIONUCLIDES,
C     INDICATOR BACTERIA), AND UN-IONIZED AMMONIA CONSTITUENTS.
C     THIS PROGRAM INCLUDES OPTIONS FOR DESIGN   QRIVER,QEFFL,TEMP & PH.
C      PROGRAM DEVELOPED BY T. P. H. GOWDA, WATER RESOURCES BRANCH
C        DATE  JUNE 1980.
C   DECLARATION STATEMENTS
C
       DIMENSION TITLE(20),C(10,50),CUI(10,50),PH(4)
       DIMENSION ARAY1(400,10),ARAY2(400,4),ARAY3(400,4)
       REAL*8 X(10),XX(10),PBK,TBK,PXWC,TXWC,A3,RKS(10),QY(50),QRS,
      1THETA,BPWR,HPWR,UPWR,QRTO,QT,QRUP(6),QEFL(6),CTDP,PHDG,VOL(10),
      2B(10),H(10).U(10),BSUM(10),TOT(10),TMP(6),RQ(11),TEMPS,PAX1,PAX2,
      3RF(10),BS(10),HS(10),US(10),BETA(10),BW(10),HW(10),UW(10),RKT(10),
      4PHI(10),R,QCP,PQX,EY(10),XCRIT,PCRIT,XEK,XMZ,PMZ,TMZ,RBK,RCRT,REK,
      5RXS,RKAV,AWCP,RFWC,XWCP,RBT,RBKG,XSCE,XSCEA,PAX1,PAX2,PW1,PW2,QCR,
      6PHWC,DELQ,XL
       CALL ERRSET(208,999,-1)
C
C   INPUT DATA
    37 WRITE(6,2)
       READ(1,3) TITLE
       WRITE(6,4)
       READ(1,*) QRS,BPWR,HPWR,UPWR,TEMPS,NTR
       WRITE(6,6)
       DO 15 I=1,NTR
    15 READ(1,*) X(I),BS(I),HS(I),US(I)
       WRITE(6,8)
       READ(1,*) (BETA(I),I=1,NTR)
       WRITE(6,80)
       READ(1,*) MQ,(QRUP(J),J=1,MQ)
       WRITE(6,82)
       READ(1,*)MT,(TMP(L),L=1,MT)
       WRITE(6,86)
       READ(1,*) MF,(QEFL(L),L=1,MF)
    35 WRITE (6,52)
       READ(1,*) AMONIA
       IF(AMONIA.LE.0)GO TO 70
       WRITE(6,57)
       READ(1,*)MPH,(PH(JPH),JPH=1,MPH)
    70 CONTINUE
       WRITE(6,56)
       READ(1,*)QCP,CEFL,CBKG,CS,THETA,RBK,XWCP
       WRITE(6,55)
       READ(1,*) (RKS(I),I=1,NTR)
C   CALCULATE FLOW & TEMP'R SCALE-UP PARAMETERS
C     DELTA=0.0001;    ALOG(1/DELTA)=(4.0*2.3026) FOR CALCN. OF BGX
       NQR=11
       NW=6
       DO 10 L=1,NQR
    10 RQ(L)=(L-1)/10.0
       WRITE(6,24) TITLE
       IRUN=0
C      BEGIN COMPUTATIONS FOR THE INPUT OPTIONS.
       DO 20 JF=1,MF
       DO 20 JQ=1,MQ
       QT=QRUP(JQ)+QEFL(JF)
       DELQ=QT/(NQR-1)
       QRTO=QT/QRS
       CA=(CEFL*QEFL(JF)/QT)
       DO 20 JT=1,MT
       CTDP=THETA**(TMP(JT)-TEMPS)
       RBT=RBK*CTDP
       IF(AMONIA.LE.0)MPH=1
       DO 20 JPH=1,MPH
       IRUN=IRUN+1
       IR=IRUN
       IF(AMONIA.LE.0)PH(JPH)=7.0
       ARAY1(IR,1)=IRUN
       ARAY1(IR,2)=QEFL(JF)
       ARAY1(IR,3)=QRUP(JQ)
       ARAY1(IR,4)=TMP(JT)
       ARAY1(IR,5)=PH(JPH)
       WRITE(6,92)IRUN
C      CALCULATE AMMONIA IONIZATION PARAMETER
       IF(AMONIA.LE.0) GO TO 34
       PKA=0.09018+2729.92/(TMP(JT)+273.2)
       PF=PKA-PH(JPH)
       PCTU=1./(1.+10.**PF)
       CSTTL=CS/PCTU
```

LIST OF MIXAPPLN PROGRAM (CONTINUED)

```
  34  WRITE(6,88)QEFL(JF),QRUF(JQ),TMP(JT),PH(JPH),CEFL,CS
      IF(AMONIA.GE.1)WRITE(6,54)CSTTL
      WRITE(6,90) (RQ(L),L=1,NW)
      DO 12 I=1,NTR
      BSUM(I)=0.
      VOL(I)=0.0
  12  TOT(I)=0.
C     BEGIN COMPUTATIONS AT TRANSECT,I.
      DO 14 I=1,NTR
C   CALCULATE B,H,U FOR DESIGN FLOW=QT, FROM LEOPOLD-MADDOCK EQNS.
      B(I)=BS(I)*QRTO**BPWR
      H(I)=HS(I)*QRTO**HPWR
      U(I)=US(I)*QRTO**UPWR
C   CALCULATE WEIGHTED MEAN VALUES BW,HW,UW FROM OUTFALL TO TRANSECT(I)
      IF(I.GE.2) GO TO 60
      XX(1)=X(1)
      BW(1)=B(1)
      HW(1)=H(1)
      UW(1)=U(1)
      BSUM(1)=B(1)*XX(1)
      VOL(1)=XX(1)*B(1)*H(1)
      TOT(1)=XX(1)/U(1)
      GO TO 62
   60 I1=I-1
      XX(I)=X(I)-X(I1)
      BSUM(I)=BSUM(I1)+0.5*XX(I)*(B(I1)+B(I))
      VOL(I)=VOL(I1)+0.25*XX(I)*(B(I1)+B(I))*(H(I1)+H(I))
      TOT(I)=TOT(I1)+XX(I)/U(I)
      BW(I)=BSUM(I)/X(I)
      HW(I)=VOL(I)/(X(I)*BW(I))
      UW(I)=QT/(BW(I)*HW(I))
C   CALCULATE PRODUCT FUNCTION FOR DECAY, RF(I), & DISPERSION FACTOR
   62 RKT(I)=CTDP*RKS(I)
      PBK=RBT*TOT(I)
      CALL PDET(PBK,TBK)
      CBKX=CBKG*TBK
      A3=(RKT(I)*XX(I))/U(I)
      R=DEXP(-A3)
      IF(I.GE.2) GO TO 64
      RF(1)=R
      GO TO 66
   64 RF(I)=RF(I1)*R
   66 EY(I)=BETA(I)*B(I)*U(I)
      PHI(I)=BETA(I)*X(I)/BW(I)
      PHDG=4.0*PHI(I)
      CMAX=0.5*CA*RF(I)/DSQRT(3.1416*PHI(I))
C  LATERAL CONC. DISTR'N AT TRANSECT,I.
      DO 16 K=1,NW
      QY(K)=(K-1)*DELQ
      IF (QY(K).GT.QT) QY(K)=QT
      PAX1=(QY(K)-QCP)/QT
      PAX2=(QY(K)+QCP)/QT
      CALL SUMSRS(PAX1,PAX2,PHDG,SUMT)
      C(I,K)=CMAX*SUMT+CBKX
  16  CONTINUE
      WRITE(6,25) X(I),EY(I),(C(I,K),K=1,NW)
  14  CONTINUE
C  UN-IONIZED AMMONIA CONCENTRATION DISTRN.
      IF(AMONIA.LE.0)GO TO 19
      WRITE(6,26)
      DO 19 I=1,NTR
      DO 17 K=1,NW
  17  CUI(I,K)=C(I,K)*PCTU
      WRITE(6,25) X(I),EY(I),(CUI(I,K),K=1,NW)
  19  CONTINUE
C     END OF COMPUTATIONS AT TRANSECT,I.
      IF(AMONIA.LE.0)CSL=CS
      IF(AMONIA.GE.1)CSL=CSTTL
C     COMPUTE BACKGROUND AVG. CONC. AT D/S WPCP.
      RKAV=-DLOG(RF(NTR))/TOT(NTR)
      AWCP=RKAV*XWCP/UW(NTR)
      CALL PDET(AWCP,RFWC)
      CBA=CA*RFWC
  76  PXWC=RBT*XWCP/UW(NTR)
      CALL PDET(PXWC,TXWC)
      CBB=CBKG*TXWC
      CAVP=CBA+CBB
C     COMPUTE BANK CONC. AT D/S WPCP.
      PW1=0.
      PW2=0.
      PHWC=4.0*BETA(NTR)*XWCP/BW(NTR)
```

LIST OF MIXAPPLN PROGRAM (CONTINUED)

```
      CALL SUMSRS(PW1,PW2,PHWC,SUMWC)
      CWCP=CBA*SUMWC/DSQRT(3.1416*PHWC)+CBB
C  COMPUTATIONS FOR MIXING ZONE PARAMETERS
      XMZ=B(NTR)/BETA(NTR)
      PMZ=RKAV*XMZ/UW(NTR)
      CALL PDET(PMZ,TMZ)
      CMZ=CA*TMZ
C     CALCULATE XSCE
      IF(CWCP.GT.CSL) GOTO 220
      CALL PARSPR(C.CSL,X,NTR.KXS,XEST,CXS)
      RXS=-DLOG(RF(KXS))/TOT(KXS)
      CALL SPREAD(CSL,CA,CBKG,RBT,CXS,XEST,XSCE,KXS,BW,RXS,UW,BETA,ITRN)
      GO TO 222
  220 XSCE=-999.0
      ITRN=0
  222 WRITE(6,50)XSCE,ITRN,XMZ,CMZ,XWCP,CWCP,CAWP
      ARAY1(IR,6)=CAWP
      ARAY1(IR,7)=XSCE
C  CRITICAL POINT RESULTS FOR QRATIO=0.2 , 0.3 & 0.4
      WRITE(6,94)
      DO 20 K=3,5
      KK=K-2
      CCRIT=-1.0E+10
C  SEARCH FOR TRANSECT NEAR WHICH CRIT. CONC. OCCURS TO FIND MOVING
C     AVG. VALUES FOR CRITICAL POINT COMPUTATIONS
      DO 18 I=1,NTR
      IF(CCRIT.GE.C(I,K)) GO TO 18
      ICR=I
      CCRIT=C(I,K)
   18 CONTINUE
      XCRIT=X(ICR)
      PCRIT=PHI(ICR)
      RCRT=-DLOG(RF(ICR))/TOT(ICR)
C   CALCULATE XL,CL & CEA BY CRIT. POINT METHOD USING MOVING AVG. VALUES
   40 QCR=4.0*RCRT*XCRIT/(PCRIT*UW(ICR))*(QY(K)/QT)**2
      XL=0.25*UW(ICR)*(-1.0+DSQRT(1+QCR))/RCRT
      XLDIF=DABS(XL-XCRIT)
      XPCT=100*XLDIF/XL
      IF(XPCT.LE.5.) GO TO 42
      XCRIT=XL
      PCRIT=BETA(ICR)*XL/BW(ICR)
      GO TO 40
   42 PQX=(RCRT*XL/UW(ICR))+(0.25/PCRIT*(QY(K)/QT)**2)
      CL=(CA/DSQRT(3.1416*PCRIT))*DEXP(-PQX)+CBKG*DEXP(-RBT*XL/UW(ICR))
      CEA=CEFL*CSL/CL
C     COMPUTE XSCEA
      IF(CWCP.GT.CL)GO TO 114
      CALL PARSPR(C,CL,X,NTR,IEK,XEK,CXK)
      REK=-DLOG(RF(IEK))/TOT(IEK)
      CALL SPREAD(CL,CA,CBKG,RBT,CXK,XEK,XSCEA,IEK,BW,REK,UW,BETA,ITRA)
      GO TO 116
  114 XSCEA=-999.0
      ITRA=0
  116 WRITE(6,96)RQ(K),XL,CL,CEA,XSCEA,ITRA
C     STORE OUTPUT IN ARRAYS
      GO TO (45,46,47),KK
   45 ARAY1(IR,8)=RQ(3)
      ARAY1(IR,9)=CEA
      ARAY1(IR,10)=XSCEA
      GO TO 20
   46 ARAY2(IR,1)=RQ(4)
      ARAY2(IR,2)=CEA
      ARAY2(IR,3)=XSCEA
      GO TO 20
   47 ARAY3(IR,1)=RQ(5)
      ARAY3(IR,2)=CEA
      ARAY3(IR,3)=XSCEA
   20 CONTINUE
C     END OF COMPUTATIONS FOR THE INPUT OPTIONS
C     PRINT SUMMARIZED RESULTS
      WRITE(6,78)TITLE
      WRITE(6,100)
      DO 48 N=1,IR
      WRITE(6,102)(ARAY1(N,J),J=1,10)
      WRITE(6,104)(ARAY2(N,J),J=1,3)
   48 WRITE(6,104)(ARAY3(N,J),J=1,3)
C  CHANGE PARAMETERS
      WRITE(6,28)
      READ(1,*) NCHNG
      GO TO(35,37,999),NCHNG
C  FORMAT STATEMENTS
```

LIST OF MIXAPPLN PROGRAM (CONTINUED)

```
  2   FORMAT(/' ENTER TITLE OF STUDY')
  3   FORMAT(20A4)
  4   FORMAT(' ENTER QRS,BPWR,HPWR,UPWR,TEMPS,NTR')
  6   FORMAT(' ENTER NTR VALUES OF X,BS,HS,US')
  8   FORMAT(' ENTER NTR VALUES OF BETA')
  22  FORMAT(2A4)
  24  FORMAT(1H1//6X,'PREDICTIONS OF RUNS FOR MANAGEMENT OPTIONS'/20A4)
  25  FORMAT(2X,F8.1,1X,F7.4,11F9.3)
  26  FORMAT(2X,'TOXIC AMMONIA ')
  28  FORMAT(/'  TO CHANGE PARAMETERS ENTER THE NUMBER STATED BELOW'/
     *'   AMMONIA  1;   TITLE  2;   END  3.')
  50  FORMAT(/5X,'XS (WITH CE)=',F8.1,3X,'NO. OF ITERATIONS=',I2,/5X,
     *'MIXING ZONE LENGTH=',F9.1,5X,'CONC=',F8.2/5X,'DIST. TO D/S WPCP='
     *,F8.1,5X,'SHORE CONC. AT D/S WPCP=',F6.2/8X,'AVG. CONC.AT D/S WPCP
     *= ',F6.2)
  52  FORMAT('   UN-IONIZED AMMONIA  ENTER 1 FOR YES; 0 FOR NO')
  54  FORMAT(5X,'  CRITERION FOR TOTAL AMMONIA, CS=',F6.3)
  55  FORMAT(2X,' ENTER NTR VALUES OF RKS')
  56  FORMAT('   ENTER QCP,CEFL,CBKG,CS,THETA,RKB,XWCP')
  57  FORMAT('   ENTER MPH AND PH VALUES')
  78  FORMAT(1H1//6X,'SUMMARY OF RUNS FOR MANAGEMENT OPTIONS'/20A4)
  80  FORMAT('  ENTER MQ & QRUP VALUES')
  82  FORMAT('  ENTER MT & TMP VALUES')
  86  FORMAT('  ENTER MF & QEFL VALUES')
  88  FORMAT(2X,'QEFL=',F7.3,2X,'QRUP=',F7.3,2X,'TEMPR=',F4.1,2X,'PH=',
     *F4.1,2X,'CEFL=',F7.2,2X'CS=',F5.2)
  90  FORMAT(/6X,'X',6X,'EY',7X,6(F3.1,6X),/)
  92  FORMAT(/'    * * RUN NO.  ',I4)
  94  FORMAT(/9X,'    CRITICAL POINT METHOD RESULTS '/9X,'QY/QT',6X,
     *'XL',8X,'CL',9X,'CEA',6X,'XSCEA',6X,'ITRN')
  96  FORMAT(9X,F4.2,4X,F6.1,3X,F7.3,4X,F8.2,3X,F8.2,4X,I4)
 100  FORMAT(//1X,'RUN#',3X,'QEFL',5X,'QRUP',3X,'TEMP',4X,'PH',4X,
     1'CAWP',5X,'XSCE',4X,'QY/QT',4X,'CEA',5X,'XSCEA'/)
 102  FORMAT(1X,F4.0,2X,F6.3,2X,F6.2,2(2X,F5.1),2X,F6.3,
     *2X,F8.1,2X,F4.2,2X,F7.2,2X,F8.1)
 104  FORMAT(55X,F4.2,2X,F7.2,2X,F8.1)
 999  STOP
      END
C
C  SUBROUTINE FOR SUMMATION OF EXPONENTIAL SERIES TERMS.
      SUBROUTINE SUMSRS(QAX1,QAX2,PFDR,SUM)
      REAL*8 QAX1,QAX2,PFDR,BGX,SBG,P1,P2,P3,P4,T1,T2,T3,T4
      BGX=2.3026*PFDR
      SBG=DSQRT(BGX)
C  DETERMINE NO. OF IMAGES REQUIRED
      AN1=(0.5*QAX1-SBG)-0.5
      AN2=(0.5*QAX1+SBG)+0.5
      AN3=-AN2
      AN4=-AN1
      NM1=IFIX(AN1)
      NM2=IFIX(AN2)
      NM3=IFIX(AN3)
      NM4=IFIX(AN4)
      NN1=1+NM2+IABS(NM1)
      NN2=1+IABS(NM3)+IABS(NM4)
      IF(NN1.GE.NN2)NN=NN1+1
      IF(NN1.LT.NN2)NN=NN2+1
C   COMPUTE SUM OF EXPONENTIAL SERIES TERMS
      SUM=0.
      DO 32 J=1,NN
      N=J-1
      P1=(QAX1-2.*N)**2/PFDR
      P2=(QAX2+2.*N)**2/PFDR
      CALL PDET(P1,T1)
      CALL PDET(P2,T2)
      IF(N.LE.0) GO TO 30
      P3=(QAX1+2.*N)**2/PFDR
      P4=(QAX2-2.*N)**2/PFDR
      CALL PDET(P3,T3)
      CALL PDET(P4,T4)
      GO TO 32
  30  T3=0.
      T4=0.
  32  SUM=SUM+T1+T2+T3+T4
      RETURN
      END
C
C  COMPUTE EXPONENTIAL TERMS  SET (P.LE.40.0) TO AVOID ERROR 208. SO
C    THAT EXP(-P)=4.3E-18.
      SUBROUTINE PDET(P,T)
      REAL*8 P,T
```

LIST OF MIXAPPLN PROGRAM (CONTINUED)

```
      IF(P.GE.40.)GO TO 10
      T=DEXP(-P)
      GO TO 12
   10 T=0.0
   12 CONTINUE
      RETURN
      END
C
C  COMPUTE PARAMETERS IN THE SUBROUTINE 'SPREAD'.
      SUBROUTINE PARSPR(C,CL,X,NTR,IEK,XEK,CXK)
      DIMENSION C(1,1)
      REAL*8  X(1),XEK
      IF(C(NTR,1).GE.CL) GO TO 75
      DO 72 I=2,NTR
      II=I-1
      IF(C(1,1).LE.CL)GO TO 73
      IF(C(II,1).GT.CL.AND.C(I,1).LE.CL) GO TO 73
   72 CONTINUE
   73 IEK=II
      GO TO 79
   75 IEK=NTR
   79 XEK=X(IEK)
      CXK=C(IEK,1)
      RETURN
      END
C
      SUBROUTINE SPREAD(CST,CAV,CBG,RB,CXY,XEY,XST,M,BI,RS,US,BTA,IT)
C   COMPUTATION OF MAX. LONGL. SPREAD,XS, ALONG OUTFALL BANK WHERE
C      (C(XS,0)-CS)=5 PERCENT(ABSOLUTE).
      REAL*8 BI(1),BTA(1),RS,US(1),PS,TS,PHB,RFS,RB,XS,PX1,PX2,TG,PG
      CXX=CXY
      XS=XEY
      IT=0
   18 IT=IT+1
      DIFF=(CXX-CST)
      RCAB=ABS(DIFF/CST)
      PRCNT=100.*RCAB
      IF(PRCNT.LE.5.)GO TO 26
      IF(IT.GT.30) GO TO 27
      FRX=RCAB/(1.0+PS)
      IF(DIFF.LE.0.0) XS=XS*(1-FRX)
      IF(DIFF.GT.0.0) XS=XS*(1+FRX)
      PHB=4.0*BTA(M)*XS/BI(M)
      PS=RS*XS/US(M)
      CALL PDET(PS,TS)
      CMM=CAV*TS/DSQRT(3.1416*PHB)
      PX1=0.
      PX2=0.
      PG=RB*XS/US(M)
      CALL PDET(PG,TG)
      CALL SUMSRS(PX1,PX2,PHB,SUMP)
      CXX=CMM*SUMP+CBG*TG
      GO TO 18
   27 XS=-888.0
   26 XST=XS
      RETURN
      END
```

A-2 TYPICAL INPUT/OUTPUT OF MIXAPPLN PROGRAM

INPUT:

```
  ENTER TITLE OF STUDY
  ENTER QRS,BPWR,HPWR.UPWR.TEMPS.NTR
  ENTER NTR VALUES OF X,BS.HS.US
  ENTER NTR VALUES OF BETA
   ENTER MQ & QRUP VALUES
   ENTER MT & TMP VALUES
   ENTER MF & QEFL VALUES
  . UN-IONIZED AMMONIA: ENTER 1 FOR YES; 0 FOR NO
    ENTER MPH AND PH VALUES
    ENTER QCP.CEFL,CBKG.CS.THETA.RKR.XWCP
    ENTER NTR VALUES OF RKS

TO CHANGE PARAMETERS ENTER THE NUMBER STATED BELOW
 AMMONIA: 1:    TITLE: 2;    END: 3.
```

```
     AMMONIA IN MIXING ZONE-GRAND RIVER BELOW WATERLOO WPCP *
12.54 .05 .5 .45 23 5
122 54.86 .62 .37
427 86.87 .62 .63
1082 44.2 .51 .55
2240 59.44 .49 .43
3398 50.29 .69 .37
.0025 .0020 .0013 .0008 .0010
1 1.132
2 20 25
1 0.307
1
1 8.3
0 12.5 0 0.02 1.106 0 20487
.0000231 .0000231 .0000231 .0000231 .0000231
3
```

OUTPUT OF MIXAPPLN PROGRAM

```
    PREDICTIONS OF RUNS FOR MANAGEMENT OPTIONS
  AMMONIA IN MIXING ZONE-GRAND RIVER BELOW WATERLOO WPCP *

 * * RUN NO.      1
QEFL=  0.307  QRUP=  1.132  TEMPR=20.0  PH= 8.3  CEFL=  12.50  CS= 0.02
     CRITERION FOR TOTAL AMMONIA, CS= 0.272

    X       EY         0.0       0.1       0.2       0.3       0.4       0.5

   122.0  0.0172    18.832    12.579     3.749     0.498     0.030     0.001
   427.0  0.0371    12.104    10.169     6.031     2.525     0.746     0.156
  1082.0  0.0107     8.906     8.018     5.851     3.461     1.660     0.645
  2240.0  0.0069     6.590     6.124     4.914     3.405     2.038     1.053
  3398.0  0.0063     4.108     3.956     3.531     2.923     2.243     1.596
TOXIC AMMONIA
   122.0  0.0172     1.383     0.924     0.275     0.037     0.002     0.000
   427.0  0.0371     0.889     0.747     0.443     0.185     0.055     0.011
  1082.0  0.0107     0.654     0.589     0.430     0.254     0.122     0.047
  2240.0  0.0069     0.484     0.450     0.361     0.250     0.150     0.077
  3398.0  0.0063     0.302     0.291     0.259     0.215     0.165     0.117

   XS (WITH CE)= 20259.4   NO. OF ITERATIONS= 8
   MIXING ZONE LENGTH=  45130.5     CONC=    0.01
   DIST. TO D/S WPCP= 20487.0     SHORE CONC. AT D/S WPCP=  0.26
      AVG. CONC.AT D/S WPCP=   0.25

         CRITICAL POINT METHOD RESULTS
     QY/QT       XL        CL''          CEA      XSCEA        ITRN
     0.20      516.0      5.946         0.57     2312.38         2
     0.30     1455.0      3.400         1.00     3956.84         2
     0.40     2575.7      2.243         1.52     5735.51         3

 * * RUN NO.      2
QEFL=  0.307  QRUP=  1.132  TEMPR=25.0  PH= 8.3  CEFL=  12.50  CS= 0.02
     CRITERION FOR TOTAL AMMONIA, CS= 0.196

    X       EY         0.0       0.1       0.2       0.3       0.4       0.5

   122.0  0.0172    18.649    12.457     3.712     0.494     0.029     0.001
   427.0  0.0371    11.815     9.927     5.887     2.465     0.728     0.152
  1082.0  0.0107     8.392     7.556     5.514     3.262     1.564     0.608
  2240.0  0.0069     5.734     5.328     4.276     2.963     1.773     0.916
  3398.0  0.0063     3.258     3.137     2.800     2.318     1.778     1.266
TOXIC AMMONIA
   122.0  0.0172     1.902     1.270     0.379     0.050     0.003     0.000
   427.0  0.0371     1.205     1.012     0.600     0.251     0.074     0.015
  1082.0  0.0107     0.856     0.770     0.562     0.333     0.159     0.062
  2240.0  0.0069     0.585     0.543     0.436     0.302     0.181     0.093
  3398.0  0.0063     0.332     0.320     0.286     0.236     0.181     0.129

   XS (WITH CE)= 14413.0   NO. OF ITERATIONS= 9
   MIXING ZONE LENGTH=  45130.5     CONC=    0.00
   DIST. TO D/S WPCP= 20487.0     SHORE CONC. AT D/S WPCP=  0.05
      AVG. CONC.AT D/S WPCP=   0.05

         CRITICAL POINT METHOD RESULTS
     QY/QT       XL        CL            CEA      XSCEA        ITRN
     0.20      481.3      5.665         0.43     2240.00         1
     0.30     1284.3      3.002         0.82     3474.97         2
     0.40     2221.0      1.872         1.31     4907.67         2


    SUMMARY OF RUNS FOR MANAGEMENT OPTIONS
  AMMONIA IN MIXING ZONE-GRAND RIVER BELOW WATERLOO WPCP *


RUN#    QEFL      QPUP    TEMP     PH     CAWP      XSCE     QY/QT      CEA      XSCEA

  1.    0.307     1.13    20.0     8.3    0.248    20259.4   0.20       0.57     2312.4
                                                             0.30       1.00     3956.8
                                                             0.40       1.52     5735.5
  2.    0.307     1.13    25.0     8.3    0.052    14413.0   0.20       0.43     2240.0
                                                             0.30       0.82     3475.0
                                                             0.40       1.31     4907.7

 TO CHANGE PARAMETERS ENTER THE NUMBER STATED BELOW
  AMMONIA  1,   TITLE  2,   END  3.
```

A-3 Instream Process Parameters used in the mixing zone study.

	QRS	BPWR	HPWR	UPWR	TEMPS	NTR	X	BS	HS	US	BETA	QCP	CBKG	RCB	XWCP
Waterloo	12.93	0.05	0.5	0.45	23.0	5	122	54.9	0.62	0.37	2.5×10^{-3}	0	0	0	20487
							427	86.9	0.62	0.63	2.5×10^{-3}				
							1082	44.2	0.51	0.55	8.0×10^{-4}				
							2240	59.4	0.49	0.43	8.0×10^{-4}				
							3398	50.3	0.69	0.37	8.0×10^{-4}				
Kitchener	12.05	0.05	0.5	0.45	24.5	8	100	62.0	1.23	0.16	1×10^{-3}	0	0	0	15047
							350	75.0	1.12	0.15	1×10^{-3}				
							600	53.0	0.40	0.62	1×10^{-3}				
							850	45.0	0.60	0.47	1×10^{-3}				
							1100	49.5	0.50	0.52	1×10^{-3}				
							1350	62.5	0.59	0.36	1×10^{-3}				
							1600	64.8	0.41	0.49	1×10^{-3}				
							1850	56.0	0.30	0.84	1×10^{-3}				
Galt	15.57	0	0.5	0.5	24.0	4	192	102.1	0.76	0.20	7.14×10^{-6}	0	0	0	50421
							701	76.2	0.79	0.26	7.14×10^{-6}				
							1170	45.7	0.65	0.53	7.14×10^{-6}				
							2015	64.0	0.46	0.53	7.14×10^{-6}				
Guelph	2.26	0	0.5	0.5	15.0	8	520	23.8	0.29	0.33	8.2×10^{-4}	0	0	0	32315
							1160	27.4	0.51	0.16	8.2×10^{-4}				
							1295	25.3	0.49	0.18	8.2×10^{-4}				
							1450	20.1	0.42	0.27	8.2×10^{-4}				
							2500	29.3	0.20	0.39	8.2×10^{-4}				
							4025	33.5	0.99	0.07	8.2×10^{-4}				
							4500	24.4	0.69	0.13	8.2×10^{-4}				

A-4 Decay Rates* for Chlorine and Ammonia below the major wastewater treatment plants in the mixing zone study

	Chlorine	Ammonia CAS Treatment	Ammonia Tertiary Treatment	Ammonia ACA Treatment
Waterloo	3.7×10^{-3}	2.31×10^{-5}	2.31×10^{-6}	-
Kitchener	3.7×10^{-3}	3.01×10^{-5}	3.01×10^{-6}	3.01×10^{-6}
Galt	3.7×10^{-3}	3.01×10^{-5}	3.01×10^{-6}	-
Guelph	3.7×10^{-3}	-	1.16×10^{-5}	-
Brantford	3.7×10^{-3}	1.16×10^{-5}	-	-

* per second at 20^{0} C (to base e)